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RESPONSE SENSITIVITY OF TYPICAL AIRCRAFT JET ENGINE FAN BLADE-LIKE STRUCTURES TO BIRD IMPACTS

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May 1982

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The response sensitivity of jet engine fan blade-like structures to the details of impact loading were studied. In particular, impacts of birds and ice on jet engines are difficult to model analytically. This report provides guidance in determining the spatial and temporal loading parameters that must be most accurately modeled in a coupled load-response analysis.

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A finite element model of a cantilever plate was subjected to various spatial and temporal loading details to determine important loading parameters. The cantilever plate was 7.62 cm (3-inches) by 24.46 cm (9.63-inches) by 3.81 mm (0.15-inches) thick. Applied loads simulated the impact load levels similar to a 85 g (3 ounce) bird impacting at 244 m/sec (800 ft/sec). The plate response was monitored by observing deflected shapes at several increments of time during and after impact.

The results show that the cantilever plate and presumably a jet engine fan blade are very sensitive to the level of momentum transfer. The detailed spatial and temporal loads that most affect momentum transfer were found to be of particular importance to the structure response.

PREFACE

The effort reported herein was conducted by the Impact Physics Group of the University of Dayton Research Institute. Mr. George Roth, Division Head of the Experimental and Applied Physics Division served as Project Supervisor. Mr. David P. Bauer, conducted the work with project supervision and technical assistance provided by Dr. Stephan Bless and Mr. Robert Bertke.

The work was performed on a subcontract basis for the Aircraft Engine Group at General Electric Company in Evendale, Ohio under Purchase Order 200-4BA-14K-47844, which is a subcontract of F33615-77-C-5221. The General Electric Program Manager was Mr. Joe McKenzie and the Principal Investigator was Mr. Al Storace.

This report covers work conducted during the period of October 1977 to January 1979 and is identified as Task II.

This report covers work conducted for project 3066, task 12, entitled Foreign Object Impact Design Criteria. The contract was sponsered by the Aero Propulsion Laboratory, Air Force Systems Command, Wright-Patterson AFB, Ohio 45433 under the direction of Sandra K. Drake (AFWAL/POTA), Project Engineer.

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INTRODUCTION

Fan and compressor blades in jet engines are subjected to damage from foreign objects ingested with the air into the engine. These blades are exposed to potential impacts from a variety of objects ranging from large birds and ice to small hard particles such as sand. The engine speed, blade material, blade geometry, point of impact, and type and size of the impactor all play important roles in determining what type, if any, and the severity of damage which might occur.

There are a great many separate phenomena which cur during slicing impacts of soft bodies (birds or ice) against target such as the leading edge of a fan or compressor blade. Bi ehave essentially as fluid slugs during impact.[1,2] In these udies, the impact of birds was demonstrated to be a nonsteady fluid dynamic process consisting of four phases: an initial shock phase in which very high pressures are generated; a shock release phase characterized by radial release of the impact shock pressures; a steady flow phase in which the bird flows onto the target; and, finally, a termination phase as the end of the bird reaches the target and the pressure decays to zero. In addition to these basic physical phenomena, there are effects due to the slice size and shape, the slicing action, and the nonplanar initial impact. If all of these effects were incorporated into a loading model, the effort required to generate and operate the model would be very complex. It is, therefore, important to conduct an analytic study to investigate the sensitivity of the response of typical blade-like structures to the details of impact loading.

This report describes the results of an analytical program undertaken to investigate the response sensitivity of typical aircraft jet engine fan blade-like structures to the details of bird impact loading. A simple cantilever plate with dimensions similar to a fan blade was modeled analytically. Finite element techniques were used to study the response of the cantilever structure to selected arbitrary loading inputs. The main loading inputs that were studied included momentum transfer, and details of spatial and temporal load distributions.

SECTION II
APPROACH

Analytical solutions of the motion of a cantilever plate loaded dynamically provided the basis for studying impact loading conditions. This section contains a description of the analytical techniques utilized for this study.

2.1 STRUCTURE DESCRIPTION

The complex geometry of a real fan blade was avoided in this study by using a flat cantilever plate. This simplification of real jet engine bird impact conditions permitted a less ambiguous study of the loading details. A flat plate 7.62 cm (3-inches) across the chord by 24.46 cm (9.63-inches) span by 3.81 cm (0.15-inches) thick was chosen as representative of medium sized jet engine fan blades. The geometry is shown in Figure 1. The material properties of type 410 stainless steel were employed in the model. As may be seen in Figure 1, all degrees of freedom of the root nodes were fixed to establish a cantilever boundary condition.

2.2 FINITE ELEMENT MODEL DESCRIPTION

A finite element code developed at UDRI was employed as the analysis tool for these studies. A brief description of this code and its application follow.

2.2.1 Code Description

MAGNA (Materially And Geometrically Nonlinear Analysis) is a large-scale computer program for the static and dynamic nonlinear analysis of complex, three-dimensional engineering structures.[3] The program is based upon the finite element method of analysis, to permit the simulation of practical structures comprised of many different types of elements. MAGNA combines

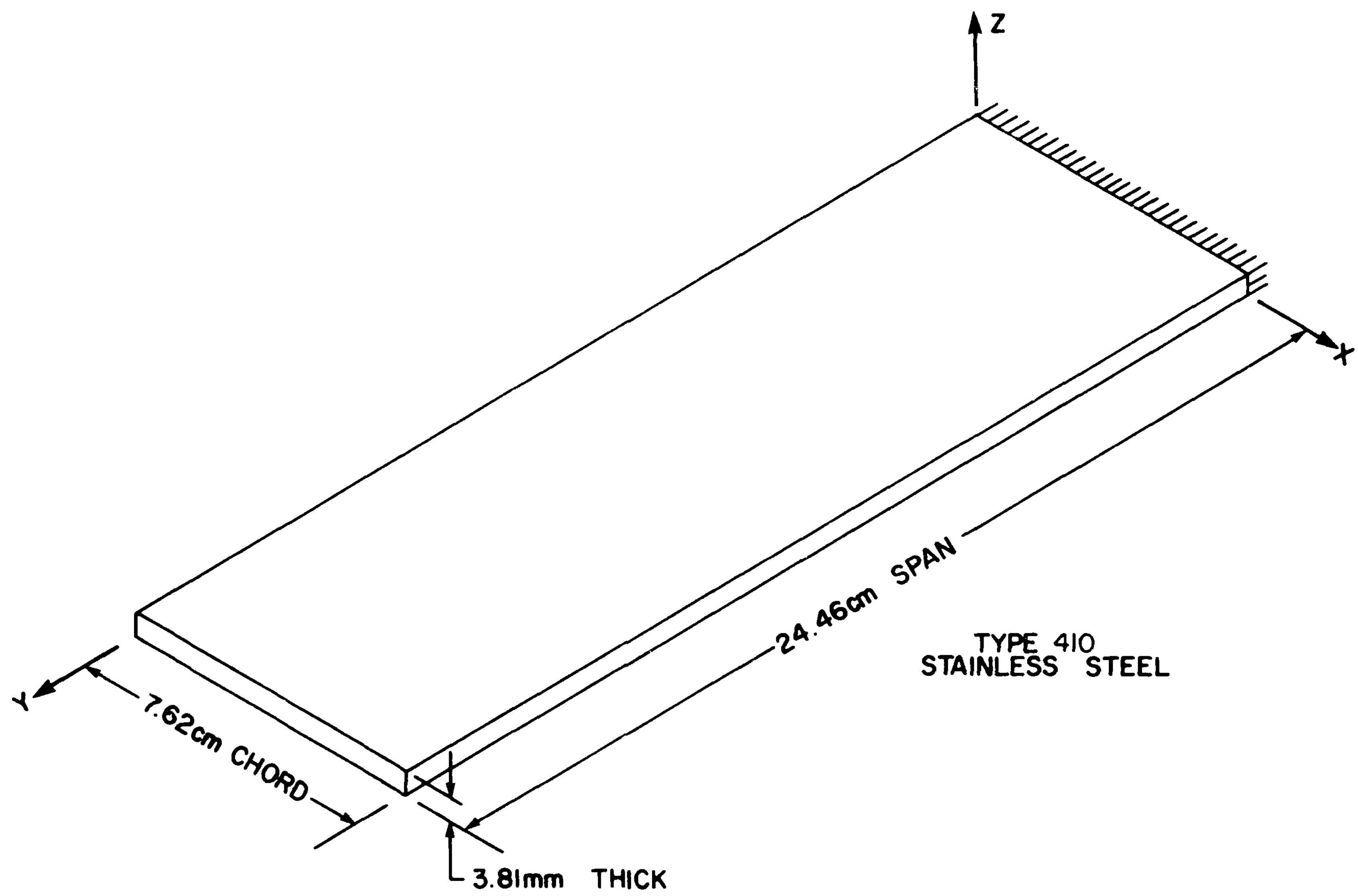

Figure 1. Cantilever Plate.

effective isoparametric modeling techniques with state-of-the-art numerical analysis and programming methods, to provide accurate and efficient solutions for problems involving highly nonlinear response.

The modeling capabilities of MAGNA include structural elements for truss members, plane stress and plane strain sections, "shear panels," general three-dimensional solids, and thin plates and shells. All elements are arbitrarily oriented and are fully compatible in three-dimensional space. Degrees of freedom can be coupled to represent skewed boundary conditions, rigid regions and complex structural joints. Uniform mass damping, as well as structural damping based upon the instantaneous stiffness, can be applied in the solution. Time history solutions are performed in MAGNA using an implicit scheme for direct integration of the equations of motion.

Each of the finite elements in MAGNA includes the effects of full geometrical nonlinearities (large displacements, large strains), using a Lagrangian (fixed reference) description of motion. In shell analysis, arbitrarily large rotations can also be treated. Material nonlinearities, in the form of elastic-plastic behavior, are analyzed using a subincremental strategy which minimizes the error in following the material stress-strain curve. Isotropic, kinematic and combined strain-hardening rules are available for use in plastic analysis with MAGNA.

The MAGNA program includes numerous user convenience features, to aid in the generation of finite element modeling data. Geometry data may be input in Cartesian, cylindrical and spherical coordinates, or in arbitrary, user-defined systems. Incremental generation of nodal coordinates and element connections is also available, to exploit repetitive patterns in the structural model. User-written subroutines, which provide for user intervention or specification of data at several stages of the analysis, can be supplied for defining mesh geometry, coordinate systems, and incremental applied loading.

Plotting utilities, in both interactive and batch forms, are also being developed for use in checking data, and for interpreting results from MAGNA. Geometry plotting, including exploded views, is currently available for all finite elements. Post processing functions which are presently provided for most element types include stress and strain contours and stress relief plots. Scaled and exploded views, or close-up plots of the deformed structural model can be generated, with the undeformed geometry optionally superimposed in the display.

The three-dimensional solid element was used to model the cantilever plate. The three-dimensional solid finite element in MAGNA is a compatible, isoparametric brick element with full nonlinear and dynamic solution capability. The geometry and deformations of the element are represented by a variable order of interpolation, which is controlled by the nodal pattern specified by the user. From 8 to 27 nodes can be used to describe the element, for maximum flexibility in specifying mesh-grading and transitions between coarse and refined regions in the model. A separate eight-node version of the element, based upon linear interpolation, is also provided for computational speed.

The MAGNA three-dimensional element can be used with reduced numerical integration, to model moderately thin shell structures, or with higher-order integration to model regions in which material nonlinearities are predominant. The order of numerical integration is controlled by the user. Consistent mass effects are included for dynamic analysis.

Full three-dimensional geometrical nonlinearities, including both large displacements and finite strains, can be analyzed using the solid continuum element. The large-displacement analysis is based upon a Lagrangian description of motion, in which all kinematic variables referred to the undeformed geometry of the structure material nonlinearities can also be considered, in the form of strain-hardening elastic-plastic flow. The uniaxial stress-strain curve of a material is represented by a number of piecewise linear segments. The plastic analysis is based upon the von Mises yield condition, and a generalized

Prandtl-Reuss flow rule. Strain-hardening materials can be modeled using isotropic, kinematic, or special combined hardening descriptions.

2.2.2 Model Description

The finite element model of the cantilever plate is shown in Figure 2. The 21 node version of the solid element with second order integration was used with the 21st node located at the center of the loaded face. The additional node on this face permitted more accurate load definition over the loaded elements. Analyses were performed accounting for both geometric and material nonlinearities. The nonlinear dynamic analysis requires considerable computing time for small time steps where a long response calculation is desired. The time step for most analyses was fifteen microseconds. This short time step dictated by solution accuracy made only early time, local response analysis practicable for the large number of analyses performed. The local response, as opposed to overall late time deflections, was determined to be more valuable as a measure of sensitivity to loading function details. The overall maximum late-time deflection of the cantilever plate was always directly proportional to the projectile momentum at impact. Thus, either bird size or impact velocity, not the details of spatial or temporal load distribution, affected the overall deflection.

2.2.3 Load Selection

The loads applied to the plate in all calculations were chosen to allow study of the effects of a particular parameter. These loads were somewhat arbitrarily chosen to provide the most advantageous analysis of the parameters in question. However, the magnitude of the momentum transfer to the plate was chosen based on real jet engine fan blade-bird impact conditions. Bertke[4] performed an analysis in which he calculated the approximate bird slice mass, relative impact velocities, and impact orientation for a bird impact into an operating jet engine. Specifically the calculations were performed for a J-79 engine operating at 7460 rpm. The forward velocity of the engine was chosen as 62.3 m/sec

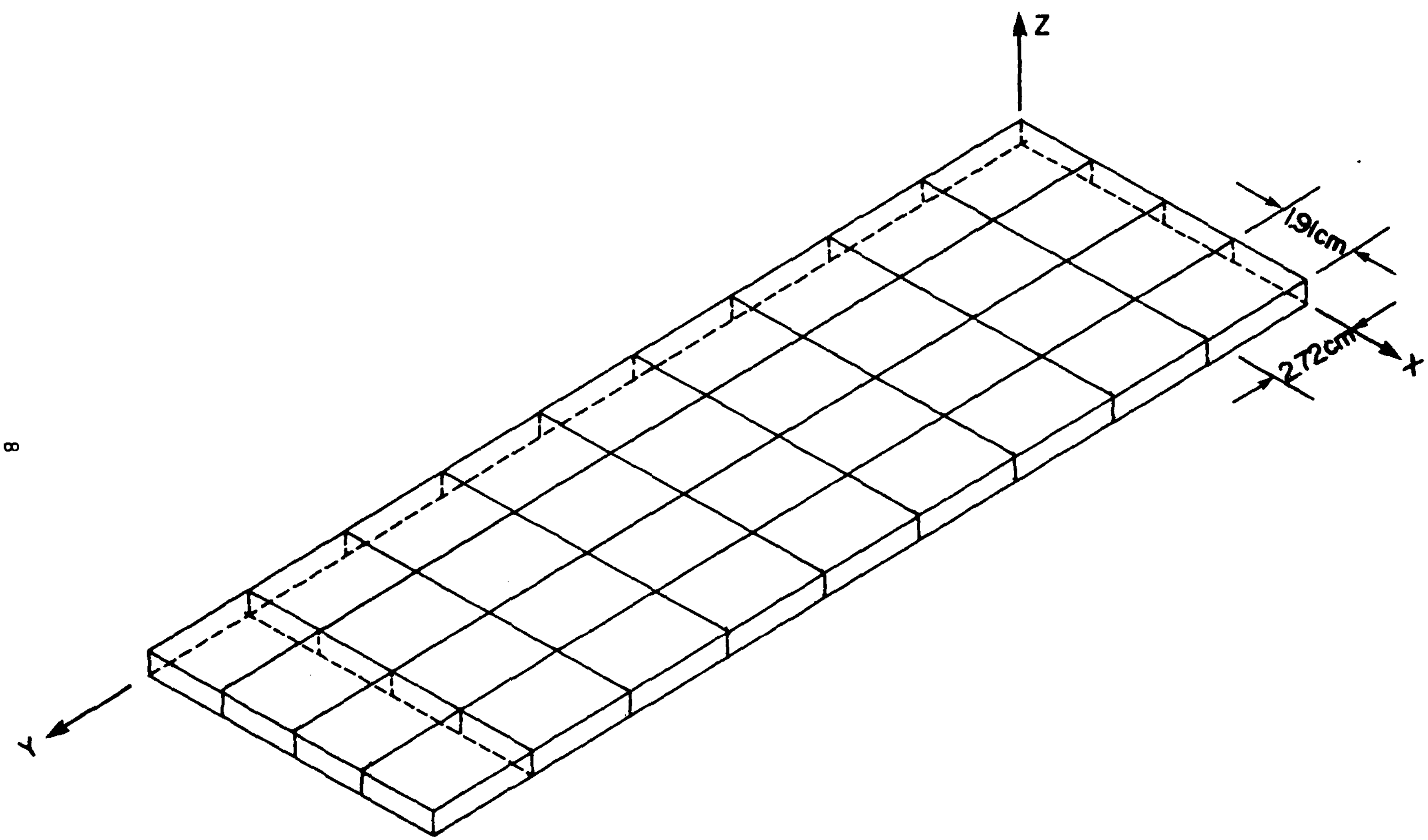

Figure 2. 3d Element Finite Model of Cantilever Plate.

(200 ft/sec) and this was used as the axial impact velocity. The calculations then determined the true relative impact velocity, orientation and maximum bird slice mass that any single fan blade could see at the stated operating conditions. A J-79 engine operating at the above stated conditions struck by a 85 g (3 ounce) starling size bird gives a slice mass of 57.153 g (0.126 pound). This is the mass that impacts the fan blade and flows off the trailing edge. During the impact, the bird velocity is changed resulting in momentum transfer to the blade. The speed at which the bird flows off the blade trailing edge is usually almost equal to the impact velocity.[1] Thus, the momentum transfer to the fan blade results from the change in direction of the bird mass that occurs. Bertke's calculations determined this angle for a 70 percent span location on the J-79 blade to be 41.9 degrees. Assuming that the speed of the bird mass is constant the momentum transfer (H) to the plate may be determined from

$$H = m(V_1 - V_2)$$

where: V_1 is the impact velocity, V_2 is the velocity of the material flowing off the trailing edge, and m is the bird mass. For the material turning through an angle $V_2 = V_1 \cos \Theta$

$$H = mV_1(1 - \cos \theta)$$

For the case described above the momentum transfer to the plate is approximately 25.7 lb_m-ft/sec or 0.8 lb_f-sec since impulse equals momentum transfer. The momentum transfer occurs in approximately the time required for the bird to travel its own length. From Bertke, the relative impact velocity in this case is 242.3 m/sec (795 ft/sec) and the bird length is about 9.14 cm (3.6-inches). Therefore, the time required for the bird to transfer the momentum to the plate is 0.38 msec.

The loads applied during the finite element calculations were based on the above considerations. The next section will describe these applied loads in detail and the subsequent results.

SECTION III
RESULTS

Cantilever plate response to the details of impact loading was studied by carefully varying only one parameter while holding all others constant. For most cases, at least two computer simulations were performed on a problem with but one parameter differing between them. This technique minimized the number of ambiguities in the comparisons of results.

The various analyses may be subdivided into six basic studies: (1) momentum study; (2) total load-duration study; (3) a force-time detail study; (4) an initial pressure study; (5) spatial distribution study; and (6) a load location study. These six studies were designed to investigate the most important elements of the impact loading process. Each study was designed to show the significance of the details of spatially and temporally resolved impact loads on a cantilever plate. The results of each of the studies will be described in the following sections.

3.1 MOMENTUM STUDY

The response of the cantilever plate to momentum transfer was studied by applying a nodal load at the 75 percent span and 50 percent chord locations. Two calculations were performed, both using step function force-time relationships. The time duration of the applied load was held at 0.4 msec for both calculations. The force magnitudes were 1000 and 2000 lb_f corresponding respectively to impulses of 0.4 lb_f-sec and 0.8 lb_f-sec impacting the plate. Figures 3 and 4 show the deflected shapes of the plate at early and late times in the deflection. The 0.8 lb_f-sec impulse resulted in a slight plastic deformation of the plate beneath the applied load point. The von Mises equivalent stresses in close vicinity to the load point reached approximately 1.1 times the

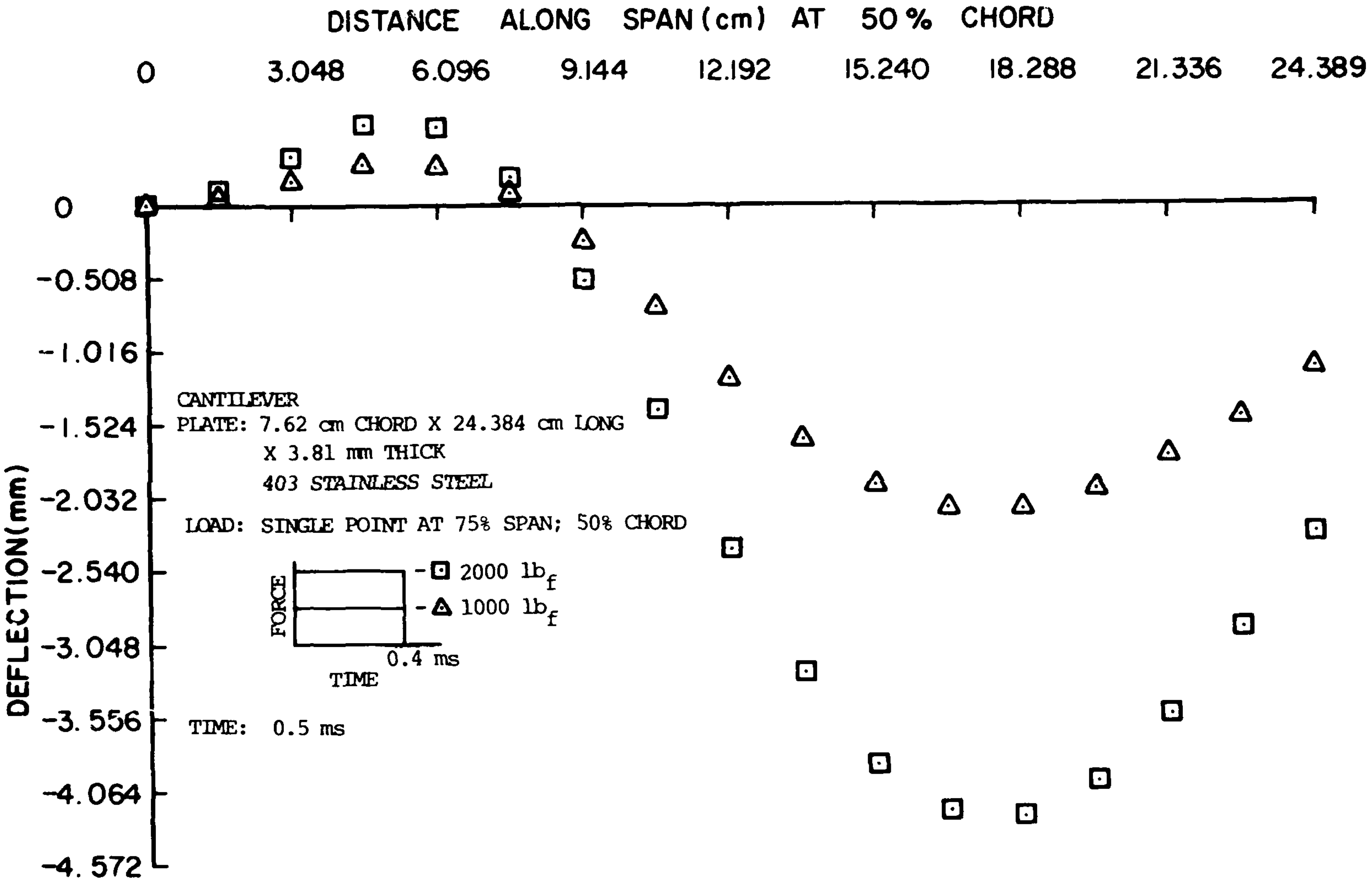

Figure 3. Effect of Two Levels of Momentum Transfer on the Early Time Deflections of a Cantilever Plate (t = 0.5 ms).

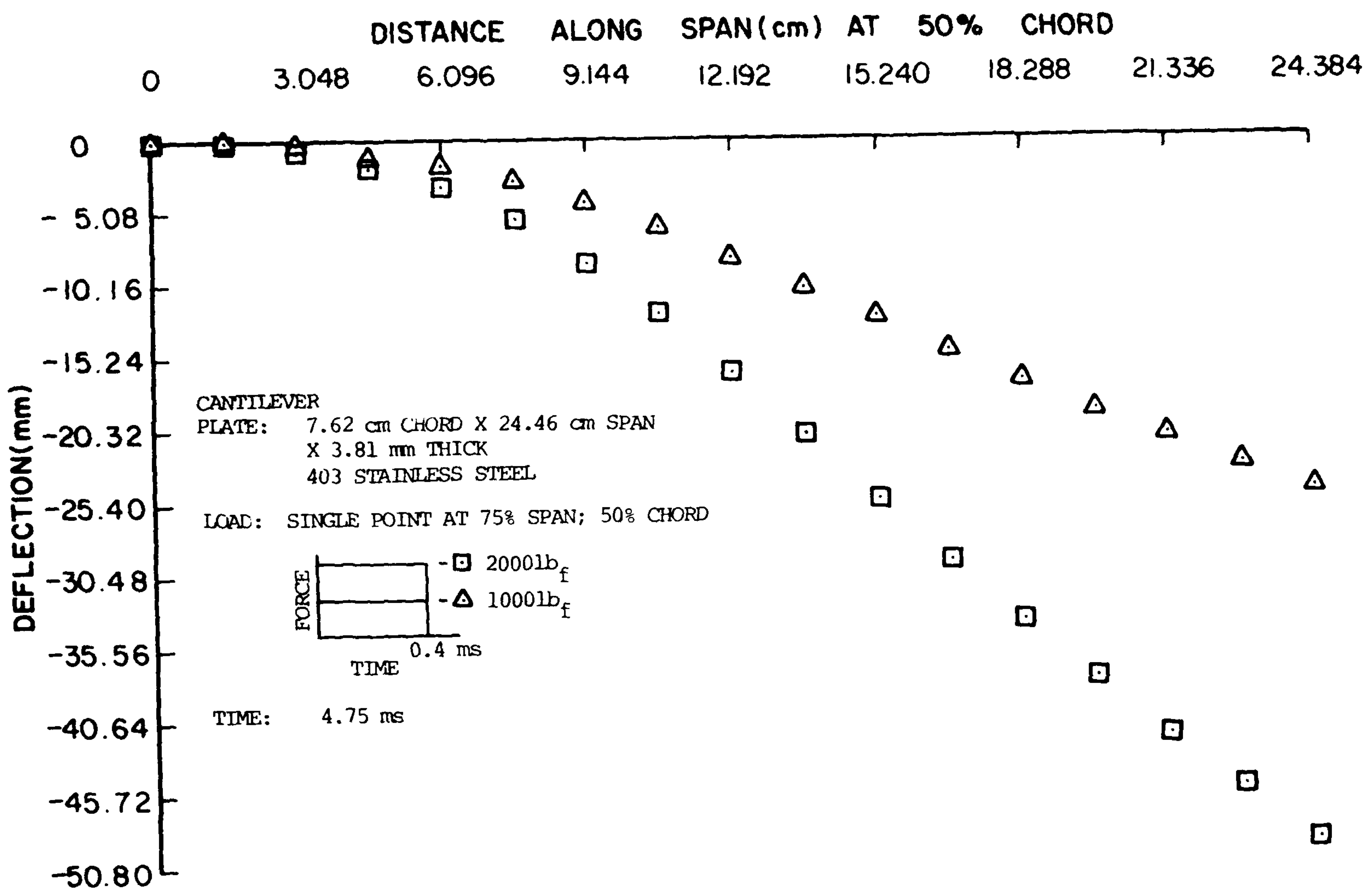

Figure 4. Effect of Two Levels of Momentum Transfer on the Late Time Deflections of a Cantilever Plate (t = 4.75 ms).

tensile yield strength for the material. As may be observed in Figures 3 and 4 the plate deflection due to the higher impulse is twice that of the lower impulse. In general, both local and overall plate deflection was directly proportional to the total momentum transfer. It may be initially concluded that any bird impact load prediction technique must accurately predict the correct momentum transfer. A failure to predict the time vs momentum transfer will certainly lead to errors in the response calculation.

The remaining sections of the report will attempt to describe the load/response effects of specific temporal and spatial parameters. This section has already shown that the overall parameters of bird mass and impact velocity must be accurately determined because these directly affect momentum transfer. The next sections will discuss the effects of load-duration on plate response.

3.2 TOTAL LOAD-DURATION STUDY

The previous section showed that momentum transfer effects on plate response for one particular load duration are important. Pressure magnitude-time duration variations that result in a certain momentum transfer, may also be important in determining plate response. The load-duration study investigated plate response by performing three calculations with the load uniformly distributed over a rectangular area 3.81 cm (1.5-inches) by 5.44 cm (2.14-inches) in each case. The center of the rectangular area was located at 78 percent span and 25 percent chord locations. This asymmetric loading was used to simulate more closely the time situation in a real jet engine during bird impact. Two of the calculations resulted in a momentum transfer to the plate of 0.8 lb_f-sec. However, in one calculation a 2000 pound load was applied for 0.4 msec while in the other a 8000 pound load was applied for 0.1 msec. The third calculation resulted in momentum transfer of 1.6 lb_f-sec with a 6000 pound load applied for 0.267 msec. The results of these calculations are shown in the deflected shape plots of Figures 5, 6 and 7 for the respective times of 0.12 msec, 0.36 msec and 0.60 msec after load application.

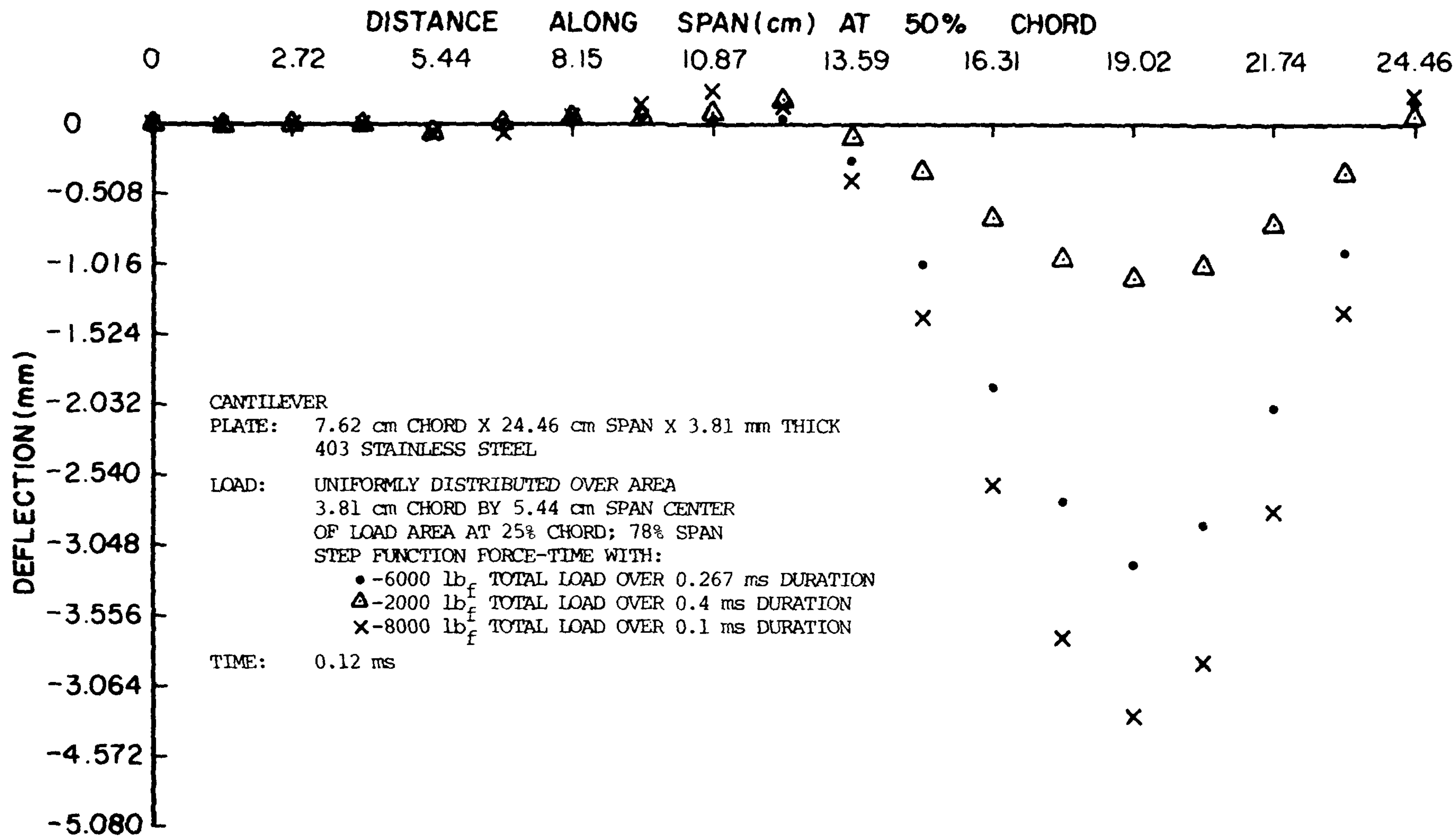

Figure 5. Effect of Load-Time Variations on the Deflection of a Cantilever Plate - Early Time (t = 0.12 ms).

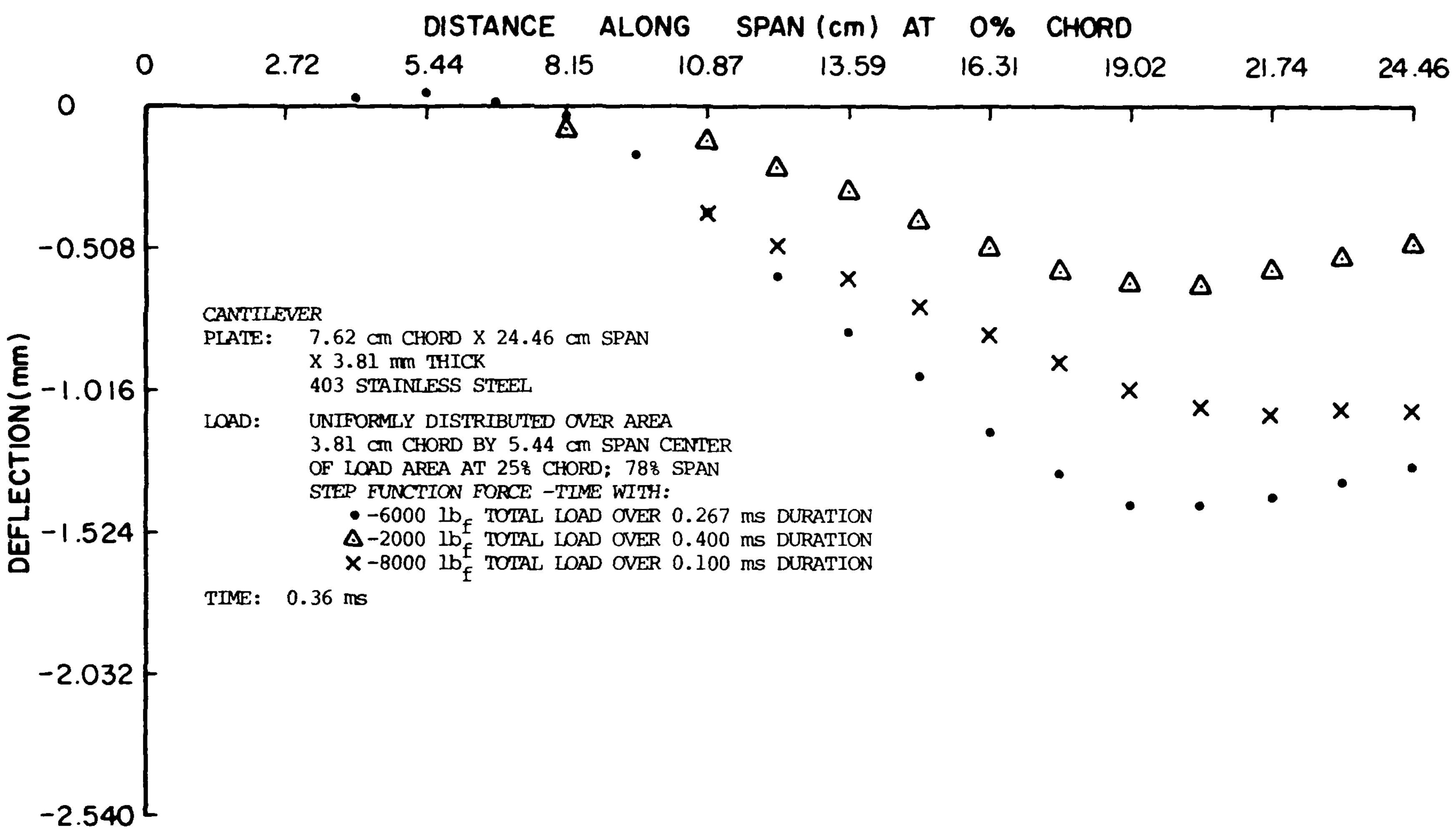

Figure 6. Effect of Load-Time Variations on the Deflection of a Cantilever Plate - Intermediate Time (t = 0.36 ms).

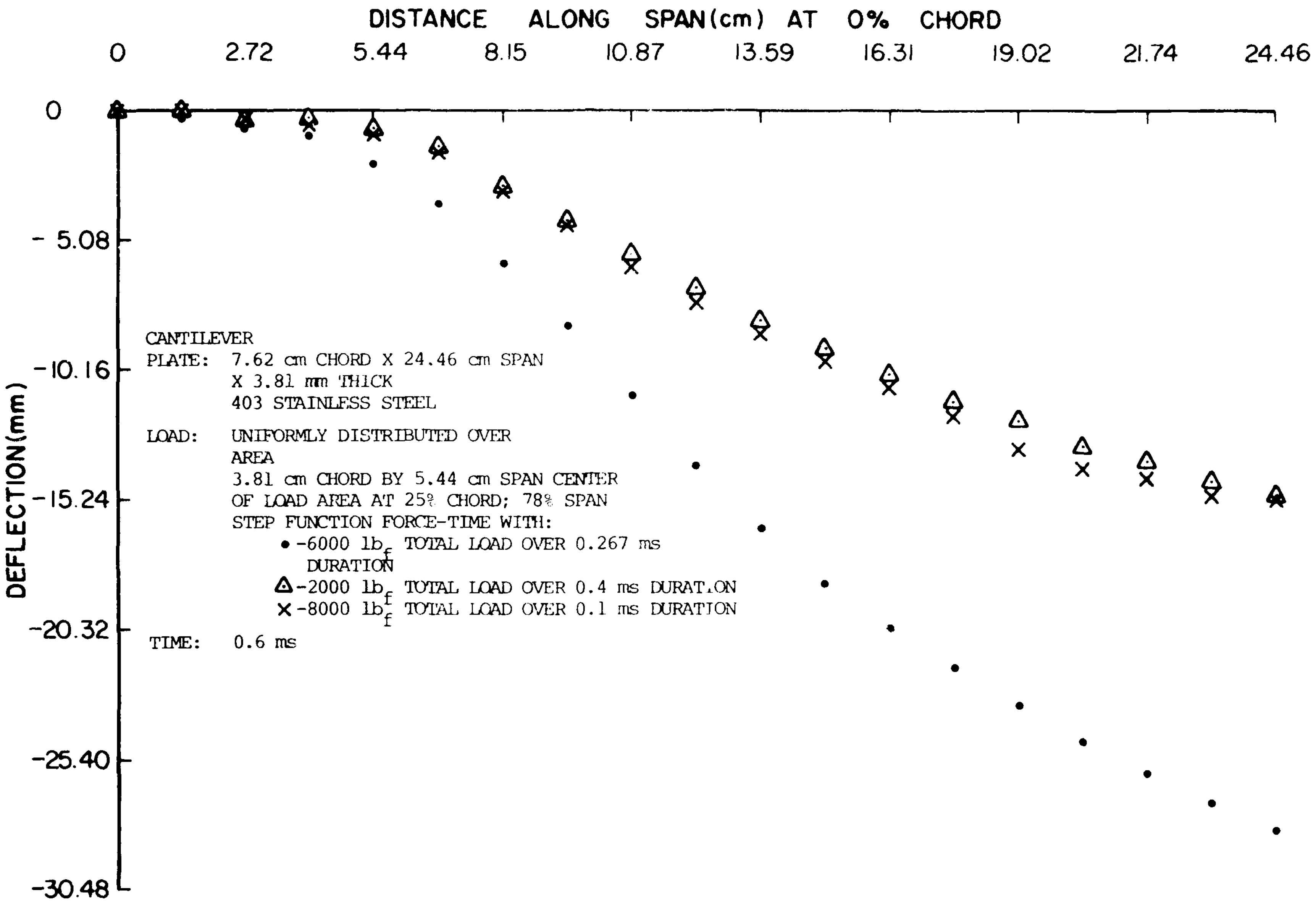

Figure 7. Effect of Load-Time Variations on the Deflection of a Cantilever Plate - Late Time (t = 0.6 ms).

Figure 5 shows that at early times the larger loads cause the greatest deflection as would be expected. Figures 6 and 7 show that the higer momentum transfer case again predominates in deflection by a factor of about two. The factor is slightly less than two because of plastic deformation. However, Figure 7 (late time after load application) shows that momentum transfer of 0.8 lb_f-sec resulted in the same deflected shape for two cases where the maximum load or pressure and load duration varied significantly.

The results discussed above and in following sections are rendered slightly ambiguous due to the nature of the cantilever plate. None of the cantilever plates modeled during this task exhibited curl-back of the "leading edge" as occurs in the case of real birds impacting real jet engine fan blades. Mainly, curl-back, more or less, did not occur because of the local-to-overall stiffness of the modeled structure. The overall stiffness of real blades is much higher than simple cantilevers due to the stiffness produced as a result of rotation (centrifugal stiffening) and also due to the camber and twist of real blades. However, the results of this study are useful in guiding further investigations.

3.3 HIGHER ORDER FORCE-TIME STUDY

Responsiveness of typical blade-like structures to change in loading will largely determine whether the force-time relationship applied for bird impact need include all the detail of true impact conditions. Thus, responsiveness could be determined in general terms by considering the inertial forces in a continuous model relative to the applied loads. However, a study of this nature is far beyond the scope of the present task. The response of a cantilever plate to the details of temporal force distributions was investigated by applying triangular shaped force-time loads to the structures. Two cases were investigated in this study. A force-time function which at zero time was zero, linearly increased to a maximum at 0.2 msec, then linearly decreased to zero at 0.4 msec. This triangular distribution is compared to a step function load in which at time zero the load was at half the triangular peak, stayed constant to 0.4 msec, then immediately decreased to zero load. In each case, a point load was applied at 78 percent span and 25 percent chord locations, and total momentum transfer was equal. The results of these calculations are shown in Figures 8, 9 and 10.

A triangular force-time function with the maximum force at time zero, then linearly falling to zero at time 0.4 msec was applied. While in the first case a linear rise in force occurred, the second had a infinitesimally short rise time. This record case was also compared to a step function applied load as above. The loads for both the triangular and step calculations were distributed over an area 5.44 cm (2.14-inches) span by 3.81 cm (1.5-inches) chord. The exact triangular spatial distributions of the load is shown in the Figures 11 and 12.

In general, the results shown in Figures 8 through 12 exhibit the same characteristics. One may observe from the results shown that the plate inertia is low enough relative to the applied loads to cause a high degree of responsiveness to the form of the applied loads. As previously mentioned, the overall to local stiffness of a real blade will be higher than the simple cantilever plate. The results shown in this section indicate that due to the responsiveness of the plate (and blade) plastic deformations could quickly occur in the plate and thus subsequently affect the remainder of the bird flow. In a case where these deformations affect the flow, a substantial change in the momentum transfer may occur. Whether or not the blade can react to the initial shocks produced at the onset of impact (as described in Reference 1) will be investigated in the next section. If these shocks can produce substantial deformations, thus changing subsequent bird flow and momentum transfer, then the loads due to the shocks must be incorporated into the coupled load-response calculations.

3.4 INITIAL PRESSURE STUDY

References 1 and 2 show that very high shock pressures occur at the bird-target interface during the initial phases of bird

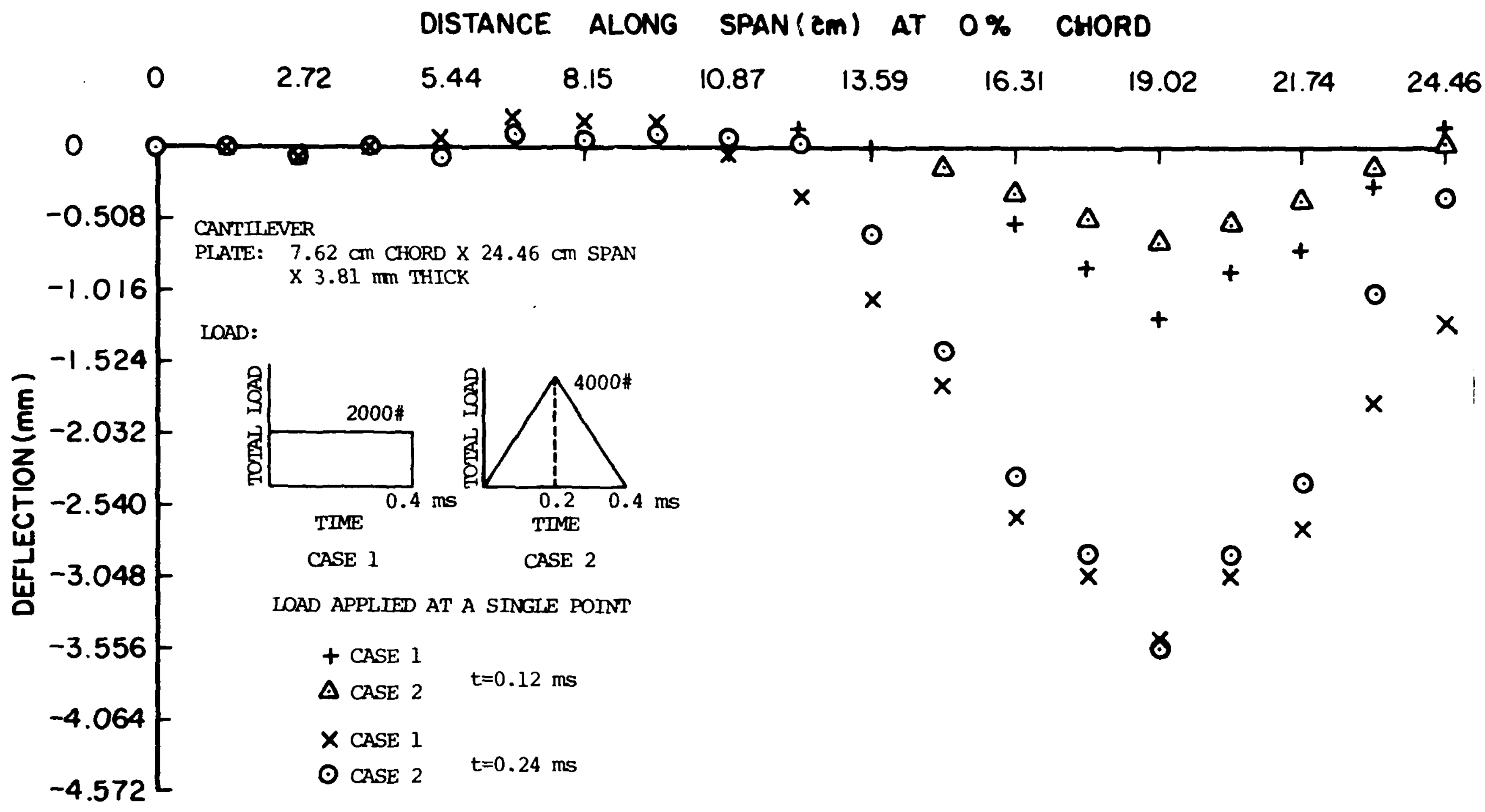

Figure 8. Cantilever Plate Response to Step Function Loads and to Triangular Function Loads (t = 0.12 and 0.24 ms).

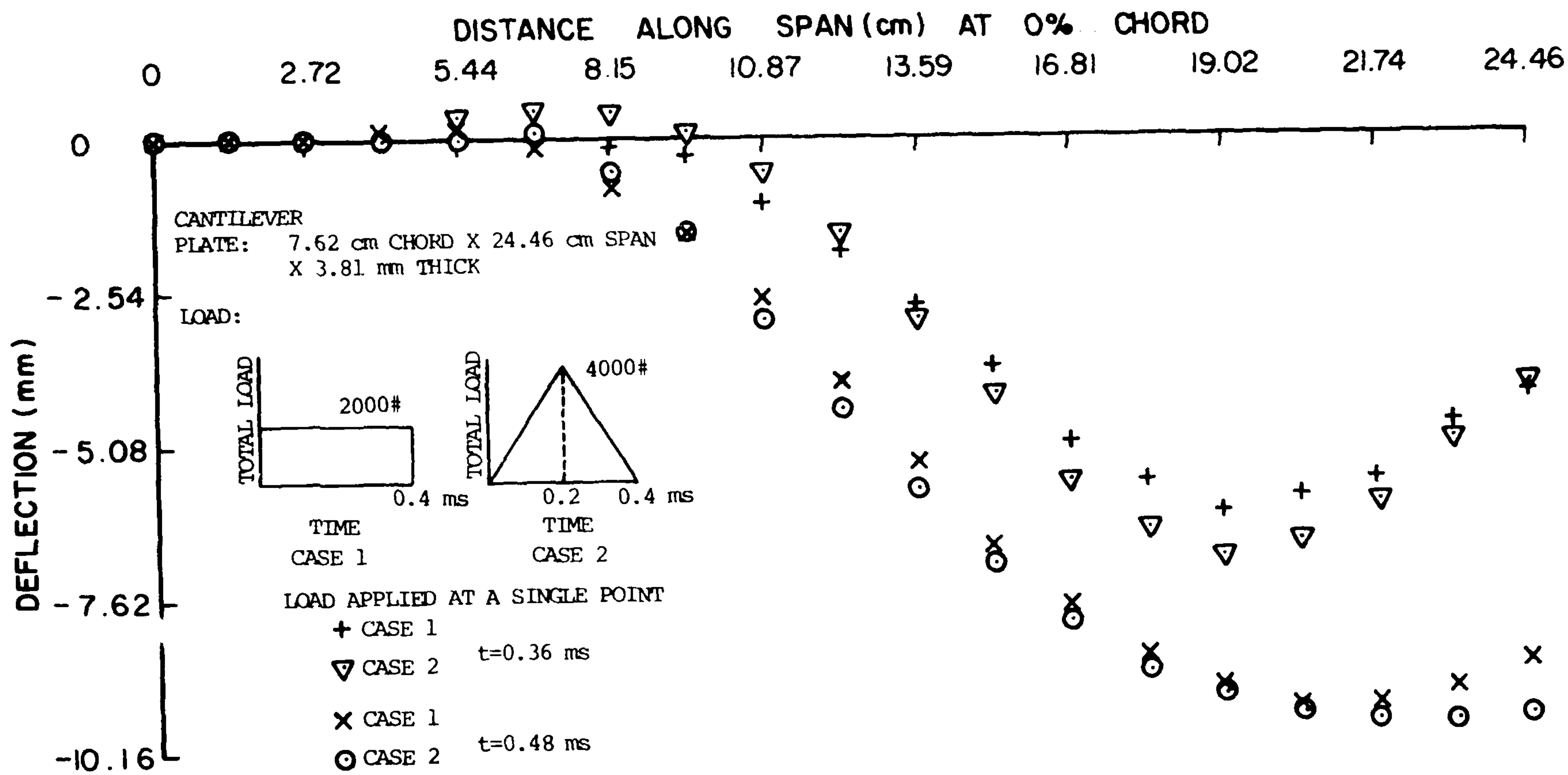

Figure 9. Cantilever Plate Response to Step Function Loads and to Triangular Function Loads (t = 0.36 and 0.48 ms).

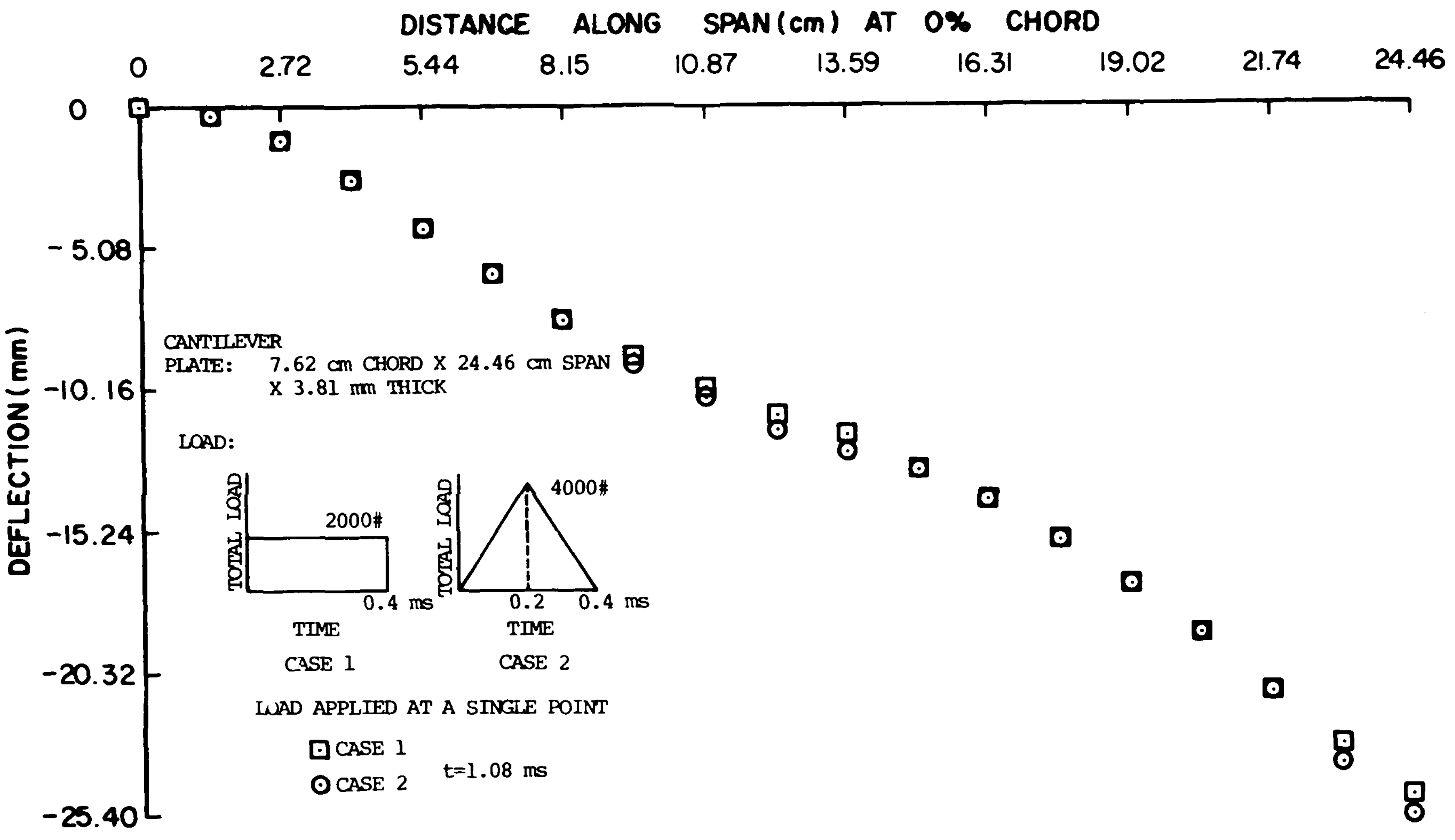

Figure 10. Cantilever Plate Response to Step Function Loads and to Triangular Function Loads (t = 1.08 ms).

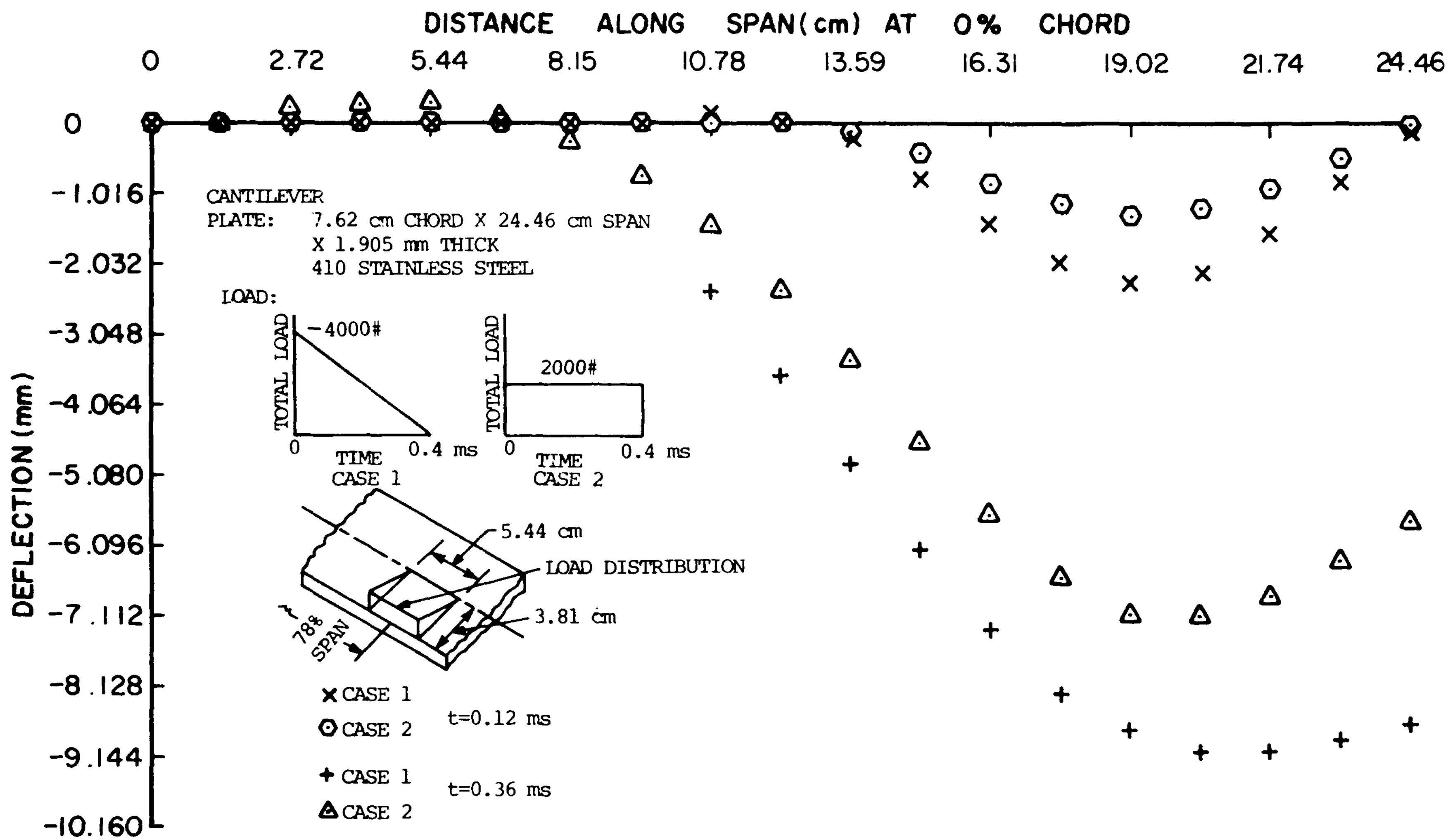

Figure 11. Cantilever Plate Response to Step Function Loads and to Triangular Function Loads (t = 0.12 and 0.36 ms).

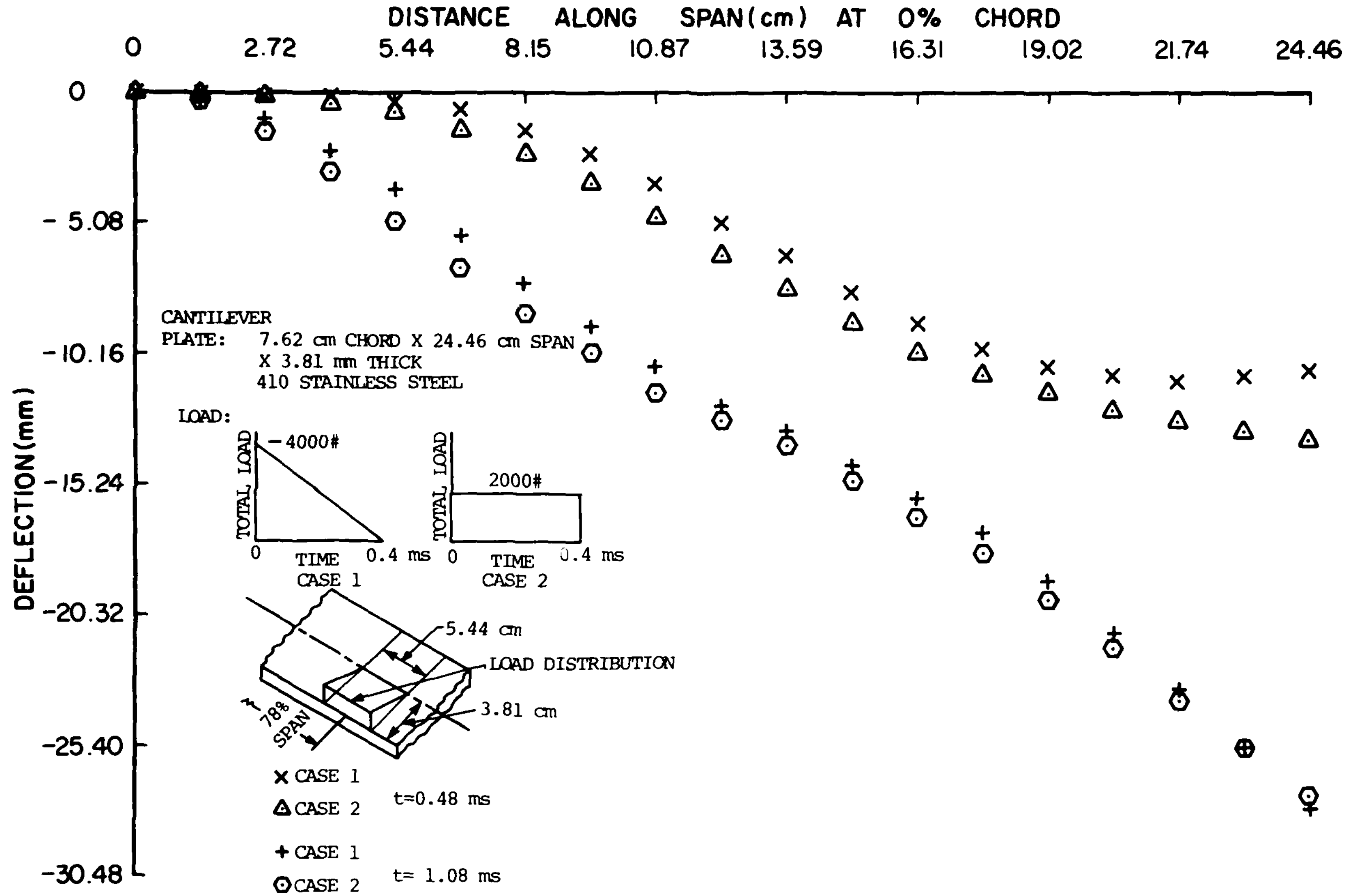

Figure 12. Cantilever Plate Response to Step Function Loads and to Triangular Function Loads (t = 0.48 and 1.08 ms).

impact. However, these references also point out that the shock pressure duration is only 10 to 15 percent of the total loading duration. Less than 10 percent of the total momentum is transferred in this shock phase. A question arises regarding the shock pressure importance on fan-blade deformation during the impact.

A study of shock pressure effects on blade deformation required the application of short duration pulses on the cantilever plate. One calculation was performed with short duration high pressure applied loads. A point load (0.4 lb_f-sec impulse) was applied in the calculation. The results are compared to a similarly applied load (spatially) with step functions temporal distribution (0.4 lb_f-sec impulse). The results are shown in Figures 13 and 14. The initial high pressure load applied for 20 percent of the total duration contained about 50 percent of the total momentum transfer. This initial momentum transfer represents a significant increase over what may actually occur in the real situation. The results show a 20 percent increase in deflection compared to the step function applied load at early time. The deflections converge at later times. Although the deflections differ at earlier times, the magnitude is small, and no apparent plastic response has occurred. These two facts lead one to believe that the early time effects on subsequent plate behavior are small when compared to the other factors already discussed. In drawing this conclusion, one must consider two other factors. In the calculation performed only one finite element is used through the plate thickness. Although the element is a higher order solid (as opposed to a shell element), it is questionable whether through-the-thickness effects of shocks could be accurately modeled. Some of the effects of the initial high pressure load may not have been detected in the analysis performed.

Coupling effects must also be considered when evaluating the results shown in Figures 13 and 14. Although only small differences of deflection are shown, it is possible that subsequent changes of bird flow result. For example, if the initial shock tends to turn the fan blade such that a large bird slice results,

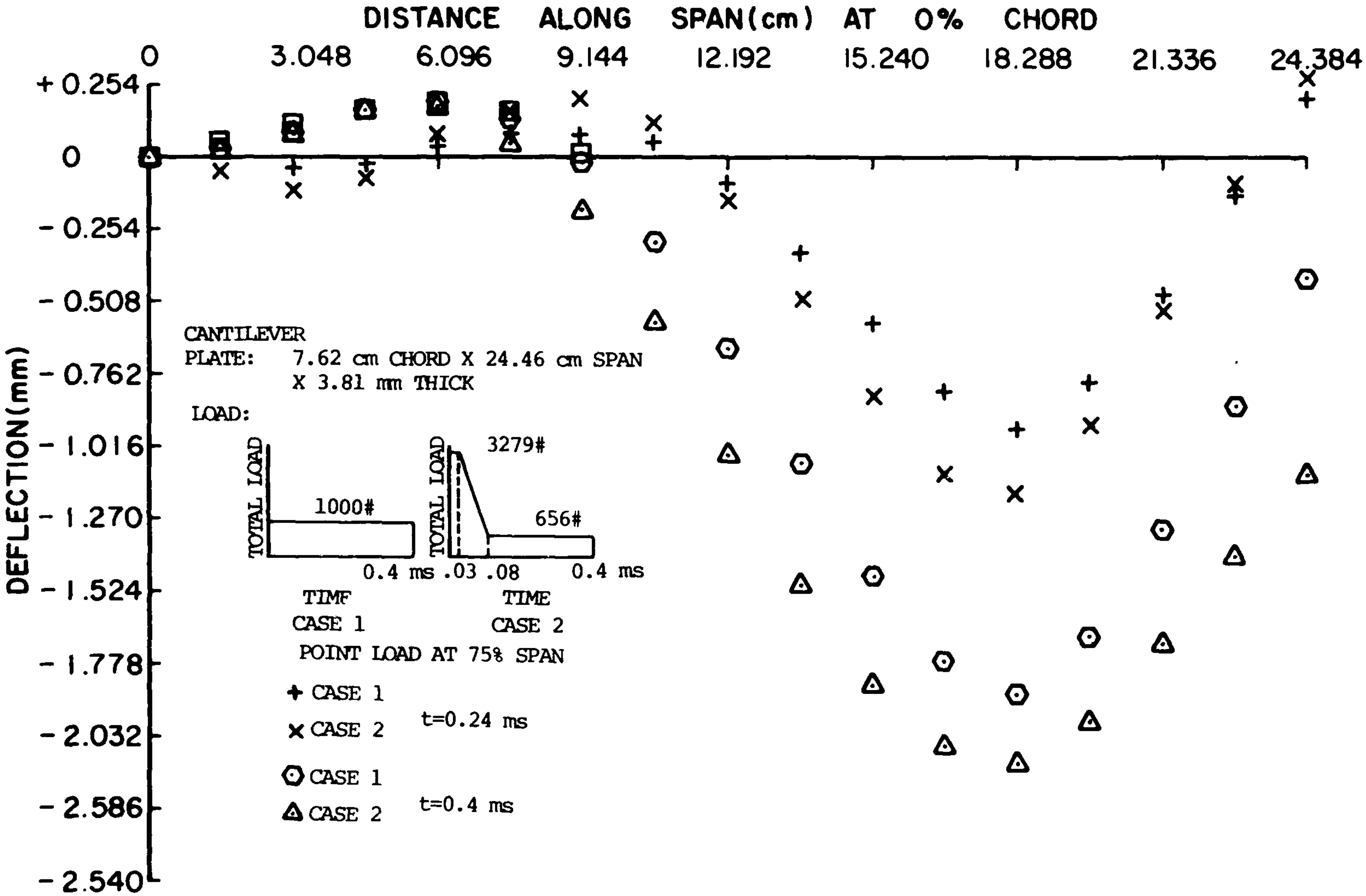

Figure 13. Cantilever Plate Response to Initial Shock Pressure Type Load (t = 0.24 and 0.40 ms).

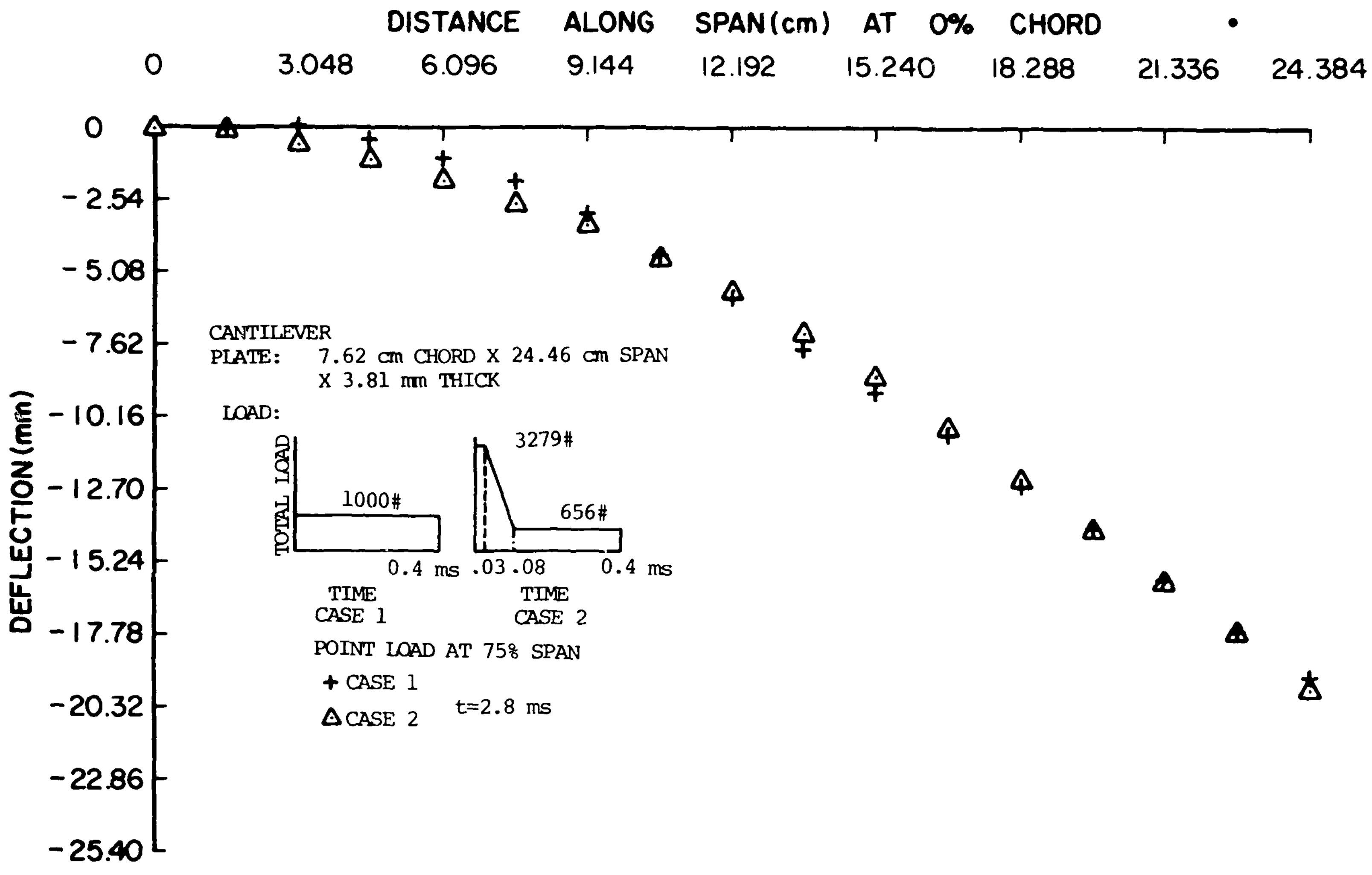

Figure 14. Cantilever Plate Response to Initial Shock Pressure Type Load (t = 2.8 ms).

then more momentum would be transferred to the blade and increased damage could result. These effects may only be studied with a fully coupled load-response model.

3.5 LOAD LOCATION STUDY

As shown in the previous section, high initial loads tended to rotate the plate in the direction of impact. It was postulated that a real fan blade exhibiting this turning action would actually result in higher momentum transfer to the structure. The turning or twisting of the plate about a span-wise axis may also be affected by the location of the load on the plate. A study was performed to compare the deflections as a result of load location on the plate.

Two sets of calculations were performed for this study. In the first study, a point load applied to 3.81 mm (0.15-inch) cantilever plates at each of two chordwise locations (i.e., load locations at 78 percent span, 0 percent chord and at 78 percent span, 25 percent chord) resulted in deflections as shown in Figures 15, 16 and 17. Figures 15 and 16 show deflected shapes at 0.12 msec, 0.48 msec and 0.60 msec along the plate span. Figure 17 shows the plate deflected shape across the chord at a span location directly under the applied loads (i.e. 78 percent span). The impulse in each case was 0.8 lb_f-sec and the both loads were applied with the same step force-time function. The figures show that application of the load closest to the edge of the plate causes a significant increase of up to 42 percent in the twisting and the span-wise local deflections. The difference in chordwise location between the two calculations is fairly large but the study does demonstrate the effect. A study that more closely simulates actual loading was also performed.

In the second investigation of response to load location, a uniformly distributed load was compared to a distributed load that linearly decreased from a maximum at the plate edge to zero at the plate chord centerline. The distributions along with results are shown in Figures 18, 19 and 20. The applied load to half-thickness 1.905 mm (0.075-inch) cantilever plates had a step function force-time distribution. The impulse in each case was 1.6 lb_f-sec. As

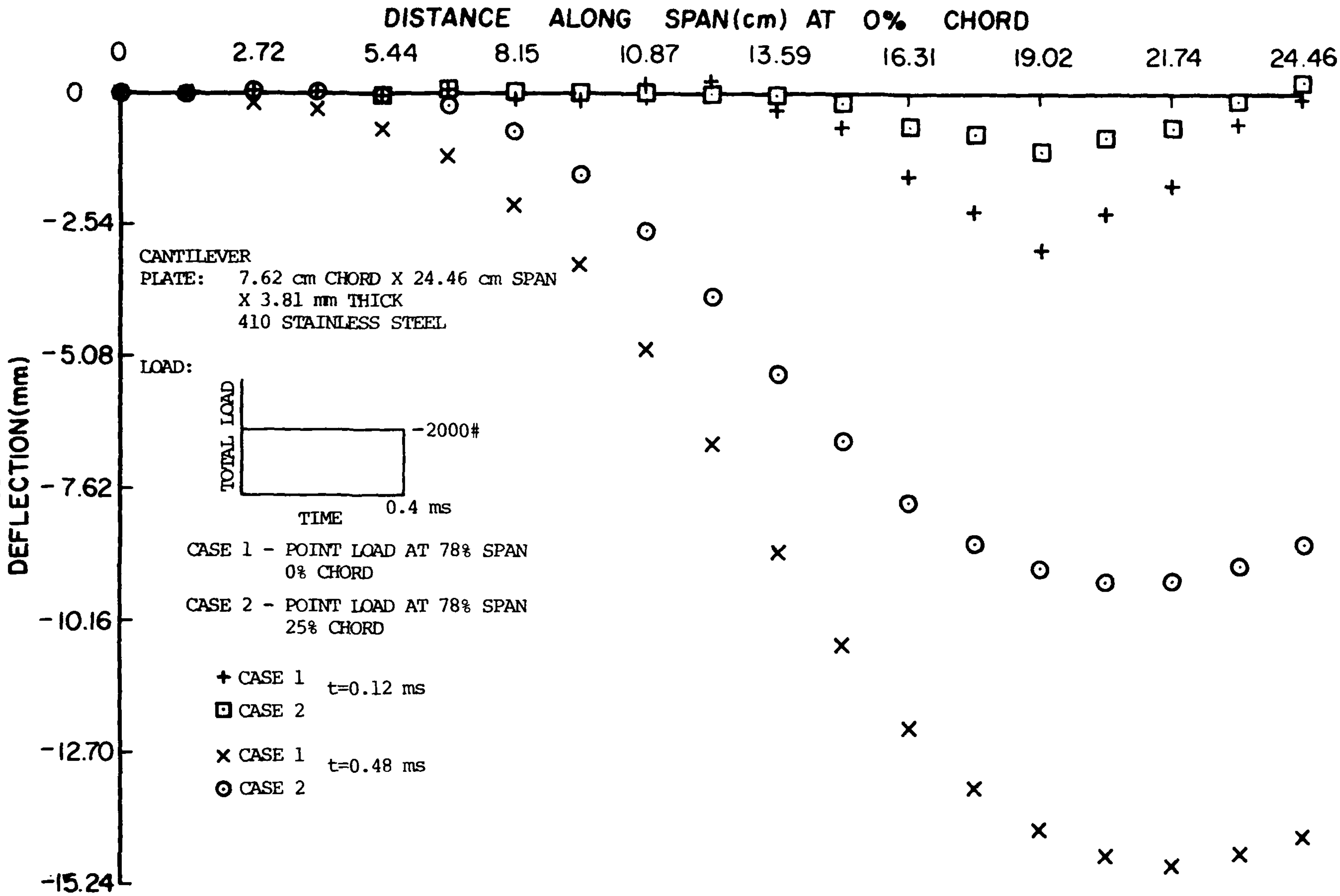

Figure 15. Cantilever Plate Response Study of Load Location (t = 0.12 and 0.48 ms).

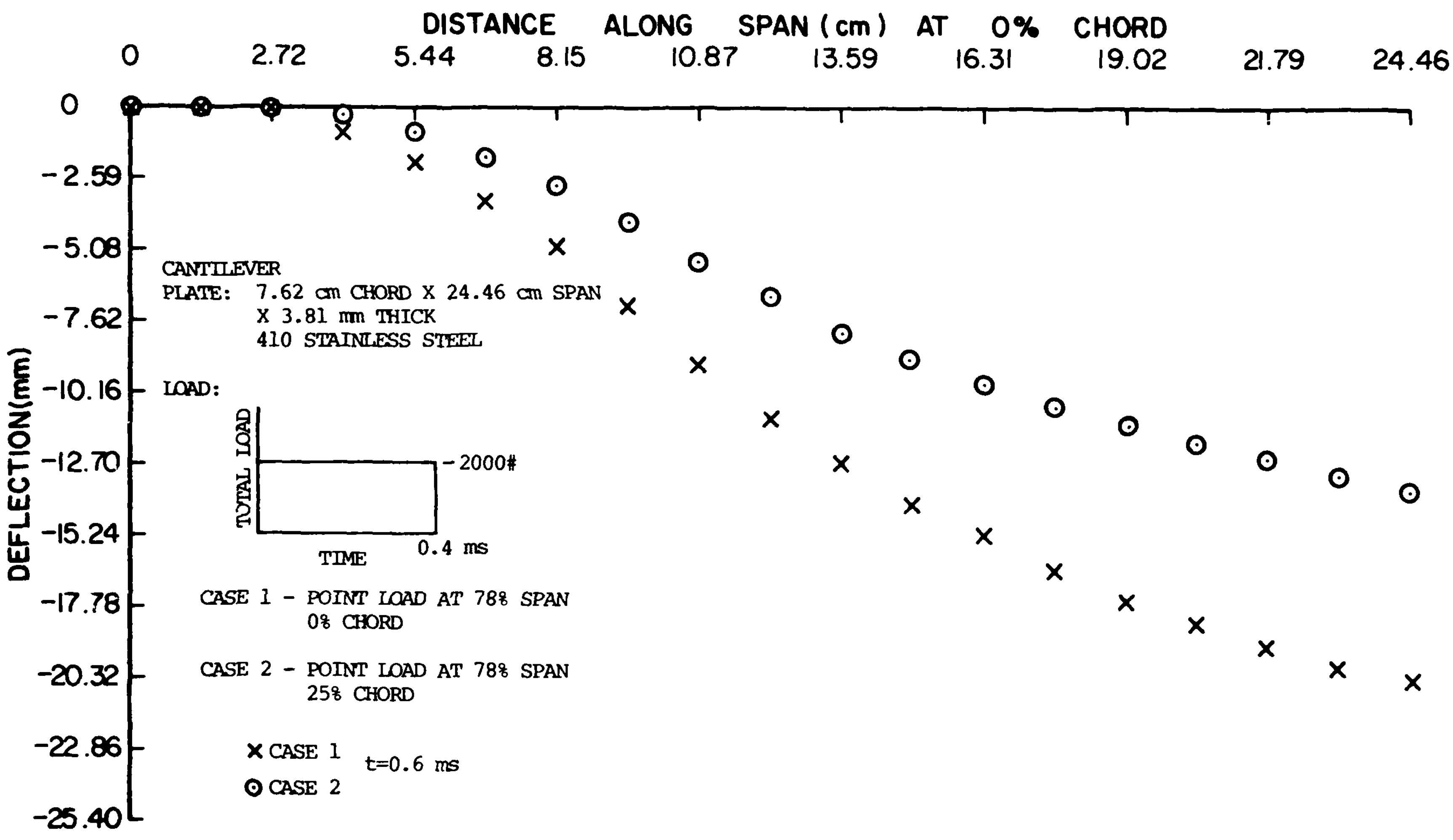

Figure 16. Cantilever Plate Response Study of Load Location (t = 0.6 ms).

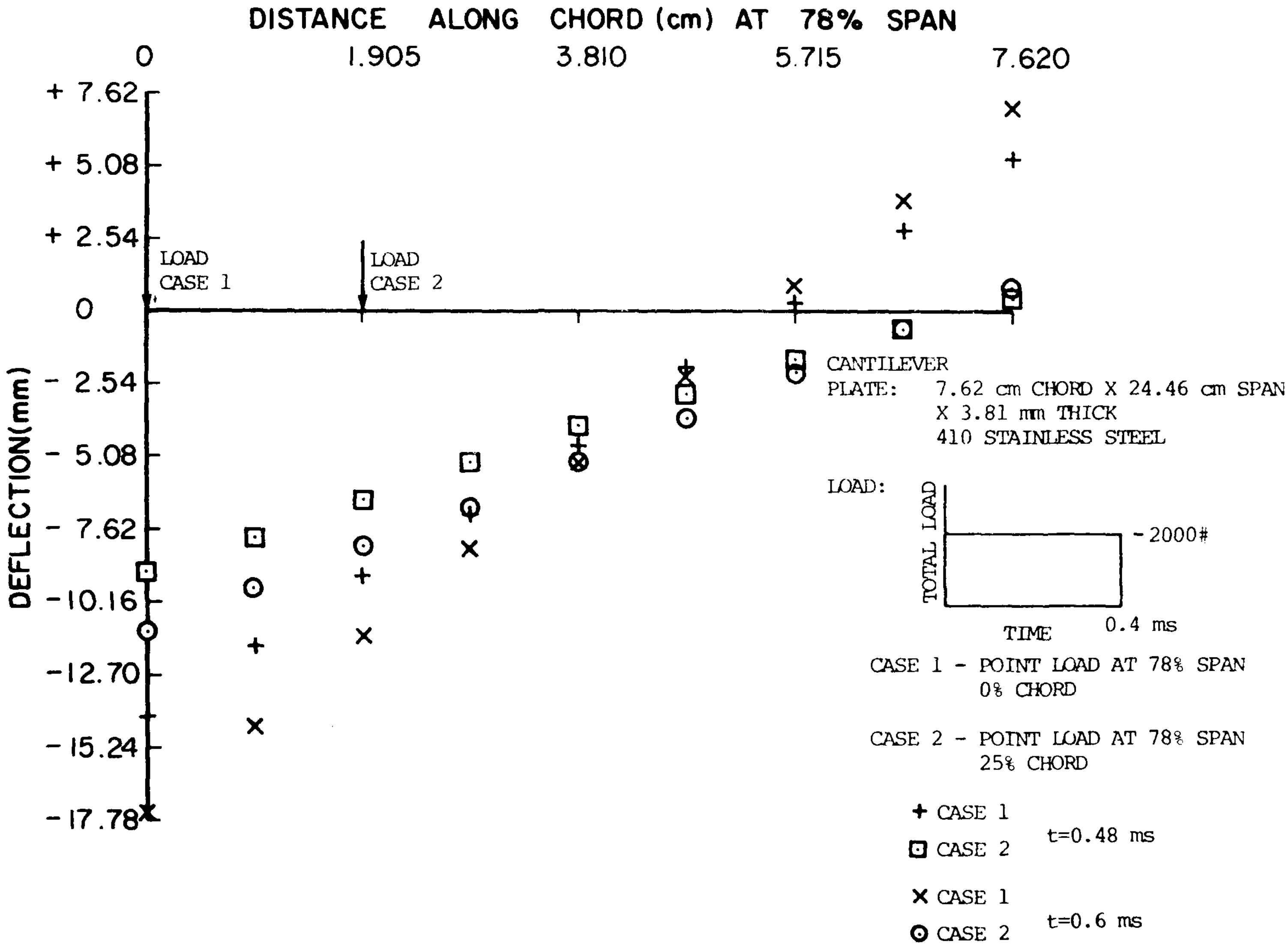

Figure 17. Cantilever Plate Response Study of Load Location (t = 0.48 and 0.60 ms).

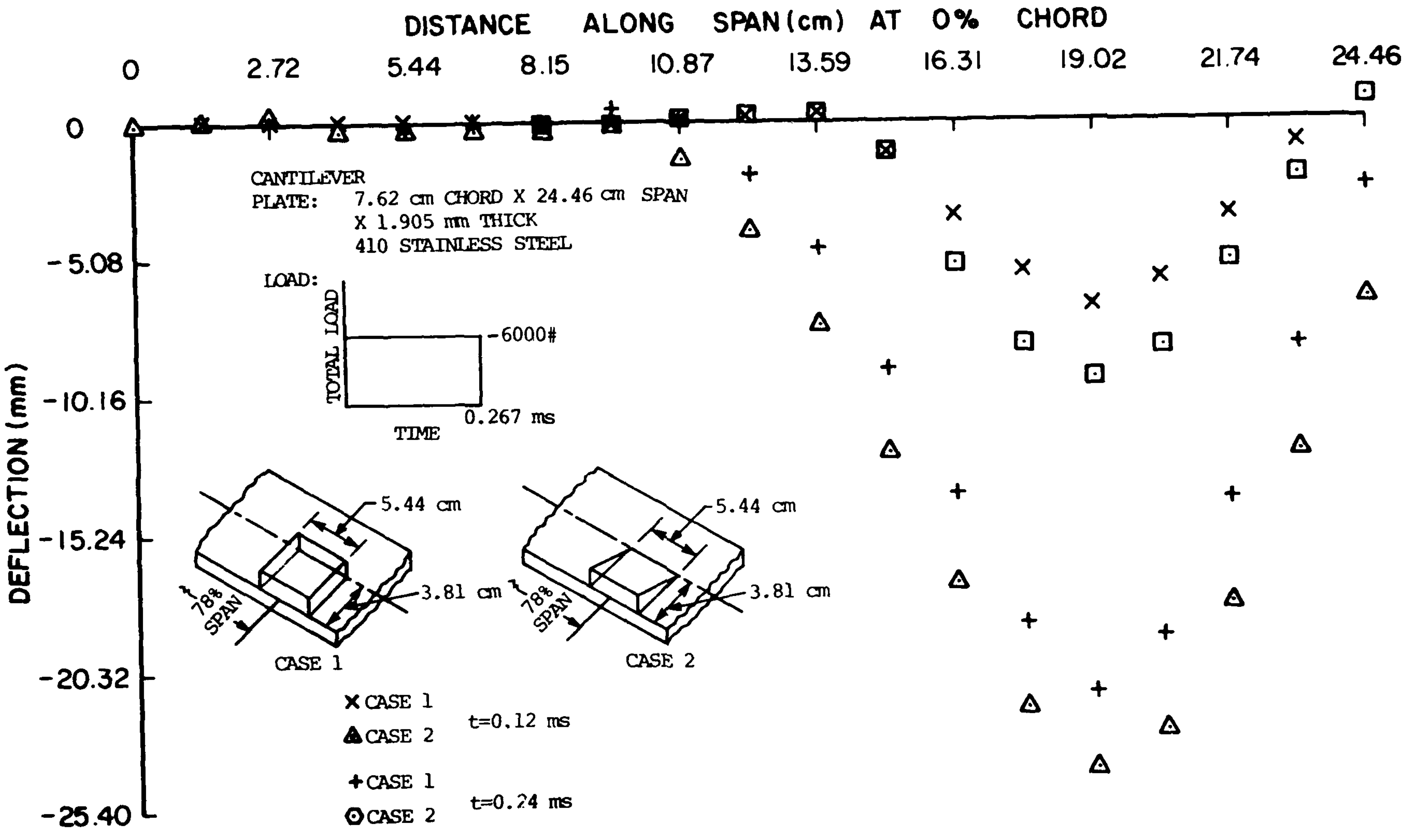

Figure 18. Cantilever Plate Response Study of Load Location (t = 0.12 and 0.24 ms).

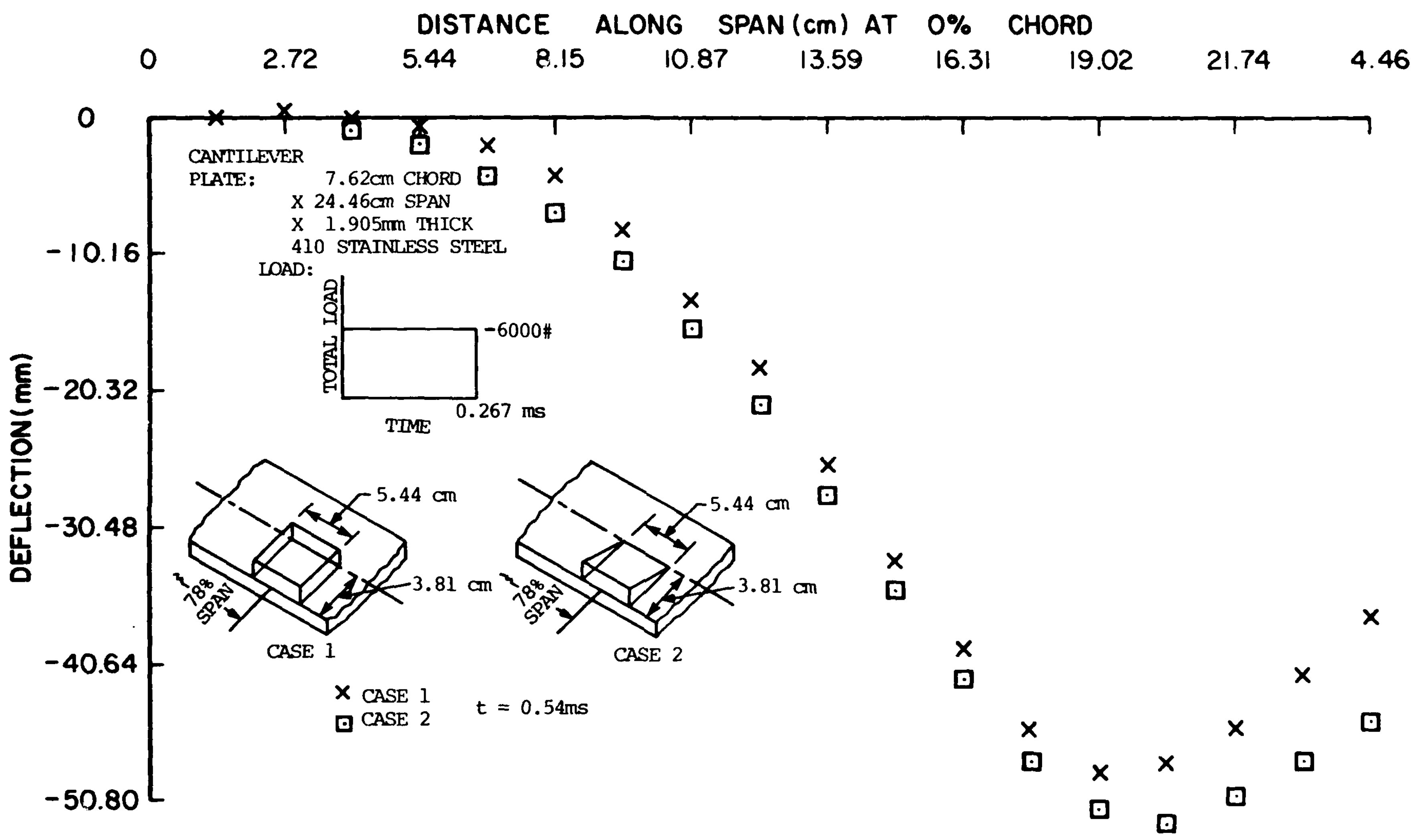

Figure 19. Cantilever Plate Response Study of Load Location (t = 0.54 ms).

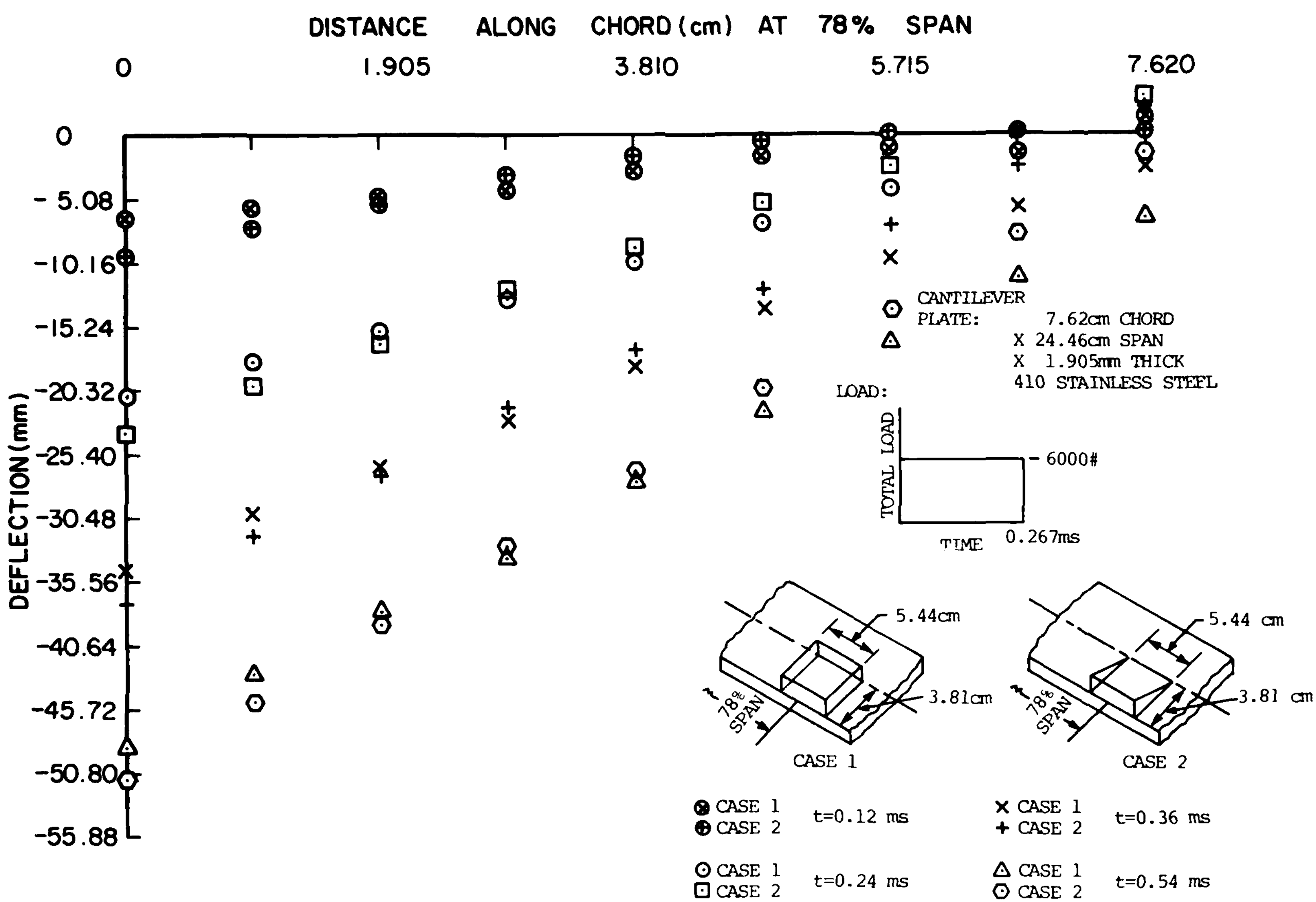

Figure 20. Cantilever Plate Response Study of Load Location (t = 0.12; 0.24; 0.36; and 0.54 ms).

may be seen in the figures, a 13 percent increase in deflection occurs for the skew distributed load. Due to this skewed load, plastic deformation takes place resulting in very high shear stresses at the plate root. In a real fan blade this effect would result in extra momentum transfer to the blade, increasing the likelihood of failure.

3.6 SPATIAL DISTRIBUTION STUDY

The effects of spatial load distribution have already been shown to some extent. This section describes a more detailed study of the subject. For these studies step function force-time loads were applied. Two levels of response both elastic and plastic were investigated. For elastic response an 0.8 lb_f-sec impulse was applied to the full 3.81 cm (0.15-inch) thickness cantilever plate. The step function load was applied from zero to 0.4 msec. In one calculation the load was applied at a single point located at 78 percent span and 25 percent chord position. These results were compared to a calculation with the applied load uniformly distributed over an area 5.44 cm (2.14-inches) along span, by 3.81 cm (1.5-inches) along the chord. The center of this rectangular area was located at the 78 percent span and 25 percent chord position. Figures 21 and 22 present the results of these calculations. As may be seen in the figures, the only significant differences between the two calculations occur at early time in the deflections. Near the end of load application (0.4 msec) the two calculations result in similar plate deflections. Due to the local stiffness of the plate, the concentrated load has only a slight tendency to produce increased local deformation over the evenly distributed loads.

In another calculation a higher impulse (1.6 lb_f-sec) was applied to a half-thickness 1.905 mm (0.075-inch) cantilever plate. The load was applied in step function form, from zero to 0.267 msec. This load was applied at a point again located at 78 percent span and 25 percent chord position. The results of the calculation are compared to the same load function applied evenly over an area 5.44 cm (2.14-inches) span, 3.81 cm (1.5-inches) chord with center

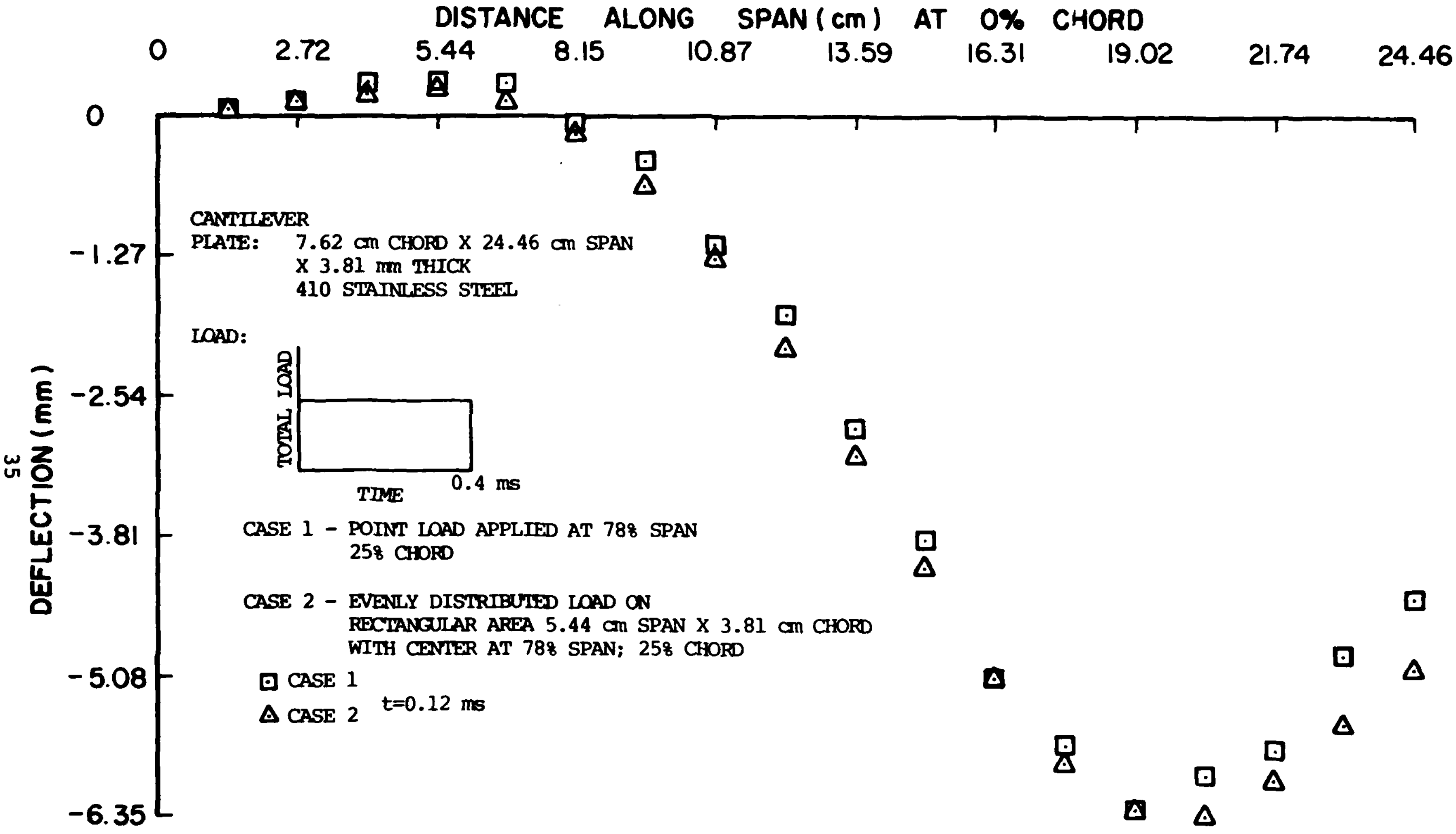

Figure 21. Cantilever Plate Response Study to Spatial Load Distribution (t = 0.12 ms).

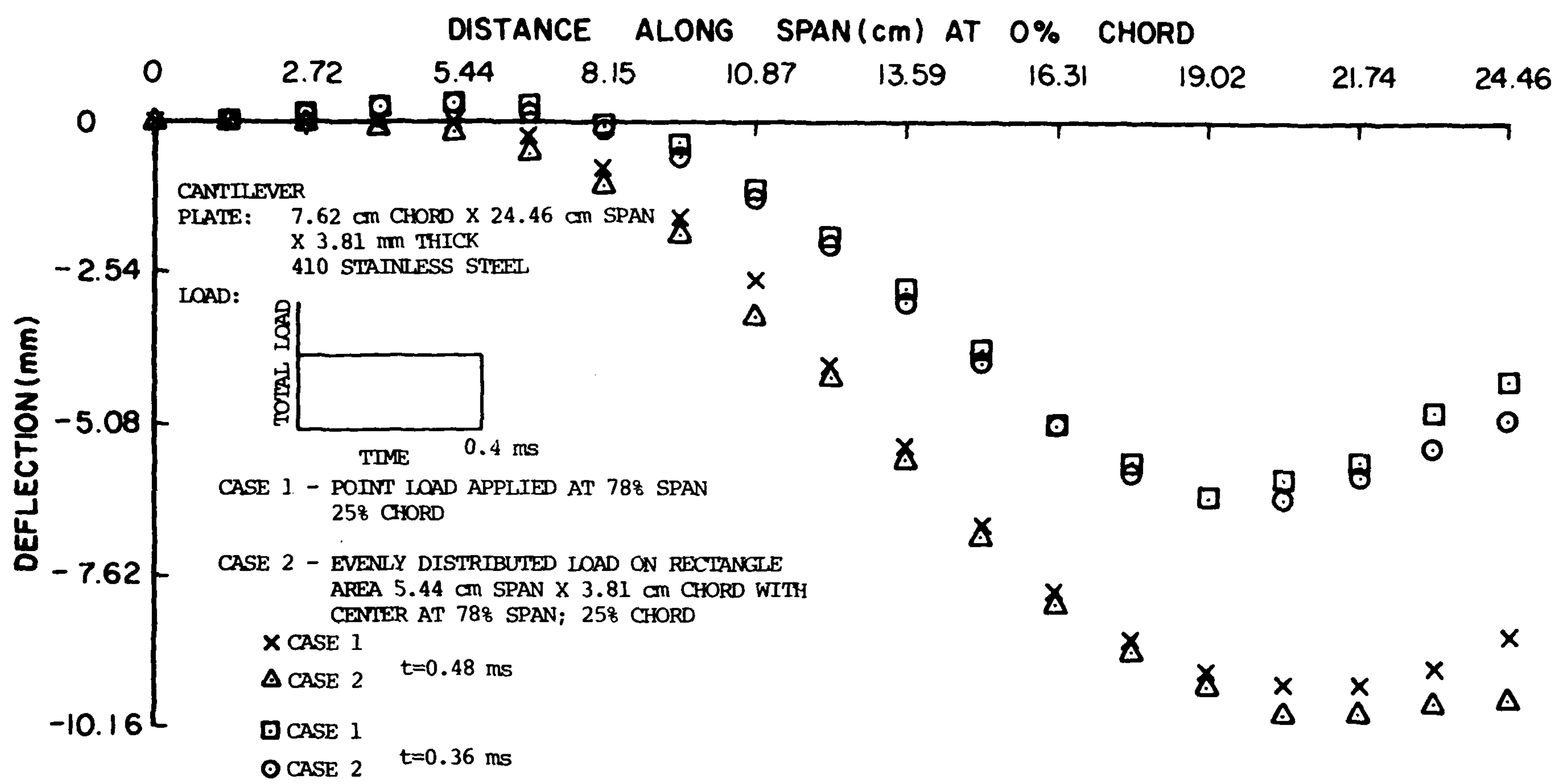

Figure 22. Cantilever Plate Response Study to Spatial Load Distribution (t = 0.48 and 0.36 ms).

at 78 percent span and 25 percent chord location. The results of these two calculations are shown in Figure 23. Comparison of the results shows that the point load causes plastic deformation in the region of the applied load. The point load does result in higher deflections but not to the extent that have been observed as a result of other factors as shown in previous sections.

The cantilever plate appears less sensitive to variations in spatial load distributions than to the temporal variations of load. Generalizing these results to the real fan blade situation is somewhat difficult due to the stiffness effects that both fan blade rotation and tip shrouds will provide. This stiffening will almost certainly magnify the effects of spatial load distribution because of the decrease in local to overall stiffness.

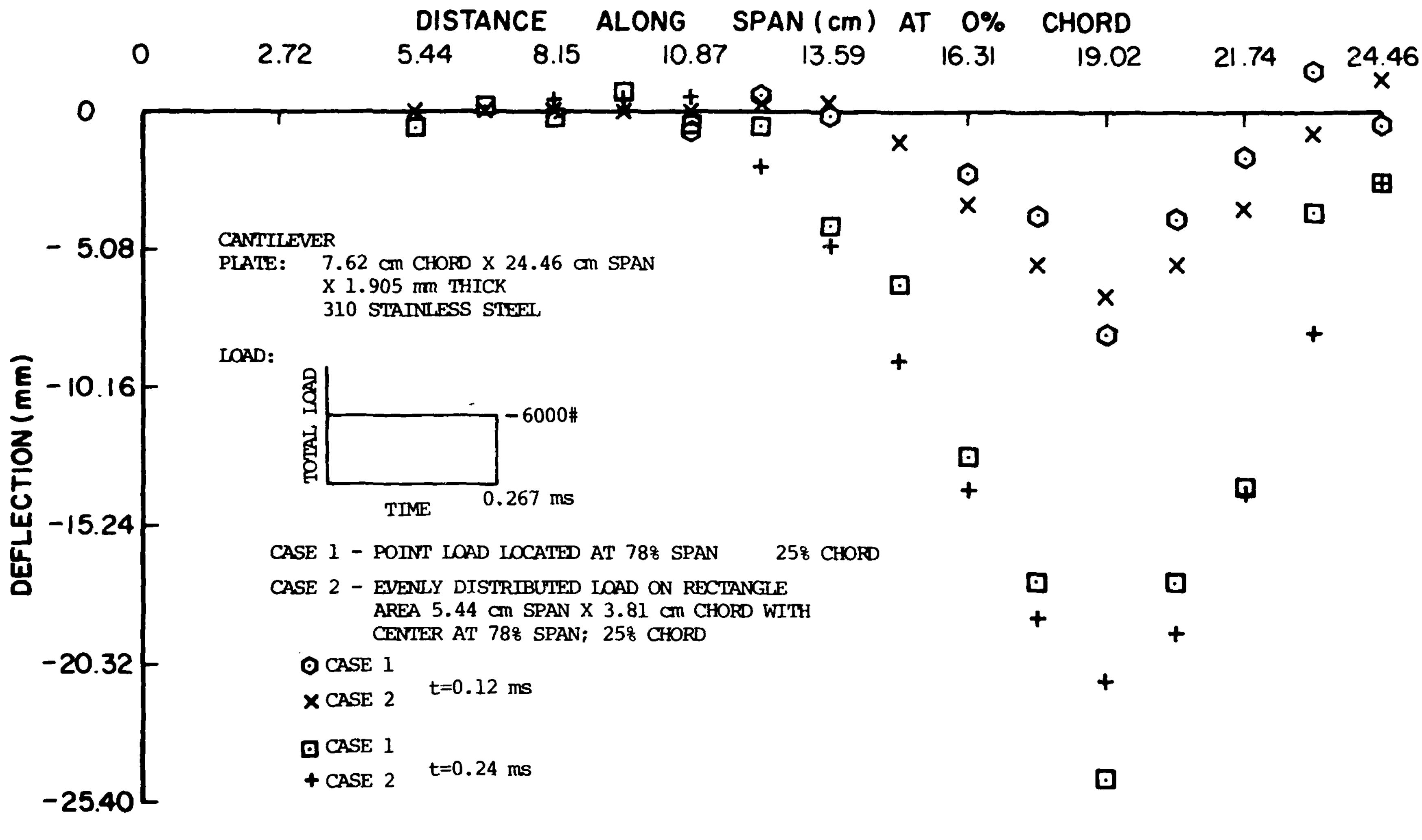

Figure 23. Cantilever Plate Response Study to Spatial Load Distribution (t = 0.12 and 0.24 ms).

SECTION IV
CONCLUSIONS

This sensitivity study has been conducted by investigating the response of a cantilever plate to various temporal and spatial load distributions. Although the jet engine fan blade has a higher overall to local stiffness than the cantilever plate most of the results found in this study should apply. These results are fully described in the previous section and are briefly summarized in the following paragraphs.

Deflections and stresses are directly proportional to momentum transfer to the structure. This result requires that a coupled load-response computer program accurately predict the momentum transfer.

The form of the applied load-duration has a direct effect on momentum transfer. The magnitude of the load must be correctly predicted especially at the beginning of impact. With incorrect initial loads on the structure, the resulting deflection will lead to further incorrect load prediction in a coupled analysis. The result will be an incorrect prediction of momentum transfer and overall deflection. The details of the force-time distribution, including the initial shock loads are the elements of the load-duration. Therefore, these details must at least be closely approximated.

The details of the spatial load distribution also have a direct effect on momentum transfer. It is very important to correctly predict the load location on the structure because the eccentric loads can cause severe twisting of the plate. The details of the spatial pressure distribution seem to have little effect on the response of the cantilever plate due to the high overall-to-local stiffness ratio. However, it was postulated that response of a real jet engine fan blade would be much more sensitive to spatial distribution due to rotational and tip shroud stiffening.

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